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Quarter-Scale Modeling of Room Fire Tests of Interior Finish

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Washington, DC 20234

March 1982

Sponsored in part by:

Ship Damage Prevention and Control
Naval Sea Systems Command
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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QUARTER-SCALE MODELING OF ROOM FIRE TESTS OF INTERIOR FINISH

B. T. Lee

Abstract

A technique for modeling fire buildup in rooms with combustible interior finish was refined to achieve closer simulation of full-scale fire development. Fire experiments were performed in one-quarter scale model rooms and full-scale rooms having a doorway opening. The interior finish test materials were nitrile foam rubber, fibrous glass, and plywood; a gas burner was employed as the fire source in a rear corner of the room. It was necessary to lower the doorway opening in the model by as much as 14 percent to obtain flashover with the same equivalent heating rate that produced flashover in the full-scale test. At the same time the width of the doorway in the model was increased appropriately to maintain the same volumetric air flow rate. The effects of burner location and heating rate on flashover in a well-insulated room were also studied to help select a suitable ignition source size and placement for testing of interior finish materials. The minimum heating rate needed to cause flashover in a 3 x 3 x 2.3 m high room lined with fibrous glass and having a 0.73 x 1.93 m high doorway opening would

entail placement of the heat source in a back corner with the source having a heat release rate of 300 kW. A corresponding rate for the quarter-scale room would be 19 kW.

1. INTRODUCTION

1.1 General

In many instances, full-scale room fire testing is the only means to realistically assess the fire performance of materials. Laboratory fire tests frequently do not predict the potential fire risk of interior finish materials under actual room fire conditions. The problem is partly with the test methods used and partly with the interpretation and application of the results. There is presently no suitable analytical prediction model for relating interior finish material fire test data to compartment fire growth, although NBS and other organizations have on-going programs to develop such a capability. Until such an analytical prediction becomes feasible, adequate selection of fire safe materials must often rely on ad hoc full-scale room fire testing. This latter procedure is expensive, especially if many materials are to be evaluated. A more economical and practical alternative is the employment of a reduced-size model room fire test for the screening of materials.

Effective scale modeling methods can contribute significantly to an improved understanding of room fire growth and, hence, help in the development of a prediction model. Fire is intrinsically an accidental occurrence, and the initiation and spread of fire in a room can occur in a variety of ways. Employment of a reduced-scale physical model is the only economical means of achieving sufficient parametric variation and physical insight for a generalized understanding of the problem. Thus, there is much incentive to develop a reduced-scale model which would predict full-scale fire performance.

1.2 Modeling Techniques

Scaling techniques with small models have been successfully applied in such diverse fire research areas as the temperature and air flow fields in large area fires [1][1] and the modeling of burning rates and flame spread by increasing ambient pressure [2,3]. Pressure modeling has also been applied for simulating enclosure fires [4]. In pressure modeling of fires, the ambient pressure is increased while the length scales are reduced according to the two-thirds power of the pressure. The two main drawbacks to this method are the problem of scaling the radiation and the need for a large and costly pressure chamber capable of handling operating pressures much above ambient conditions. Two other reduced-scale modeling methods which have been used for simulating room fire buildup cannot properly handle the contribution of combustible walls and ceilings. One of these, developed at the Illinois Institute

[1] Numbers in brackets refer to the literature references listed at the end of this report.

of Technology Research Institute (IITRI) [5], requires a constant ratio of heat release rate to the volumetric rate of air inflow in order to maintain the same temperature in the room. When the horizontal dimensions of the prototype compartment are reduced by a scale factor, the ITTRI modeling criteria require that the vertical dimension should be proportional to the scale factor raised to the two-thirds power and the rate of heat release be proportional to the square of the scale factor. Thus, the rate of heat release is proportional to the floor area but not to the wall area. If it is assumed that the mass burning rate of a combustible wall is proportional to its area, then the heat release rate of the wall material will exceed the requirement that it be proportional to the floor area.

Factory Mutual Research Corporation approached the room fire scaling problem from dimensional analysis considerations [6]. Their findings indicate that the temperature and gas compositions in a room scale reasonably well for geometrically similar enclosures where the heat release rates are proportional to the 5/2 power of the scale factor. This method assures that the ceiling of the model and prototype are at homologous points of the convective column generated by the flame. However, since the interior surface area of a room is proportional to the square of the scale factor for geometric scaling, the fuel contribution from a combustible wall is too large for correct scaling using this approach.

At the National Bureau of Standards a model having geometrically scaled room dimensions has been effective in modeling fire buildup in rooms with combustible walls and ceilings [7]. This modeling procedure assumes that the severity of a room fire can best be described in terms of the temperature of the hot air layer below the ceiling. The hot air layer, as the term is used here, includes flaming and non-flaming gaseous pyrolysis and combustion products. When this air temperature reaches 500°C there is rapid pyrolysis of the combustibles in the upper part of the room. When this temperature reaches about 650°C there is sufficient radiation into the lower part of the compartment to ignite virtually everything combustible. The maximum temperature which can be reached with a given set of lining materials, furnishings, and ventilation can be identified as the "fire buildup potential" of the compartment. The estimation of the fire buildup potential of a room then is based on a prediction of the maximum temperature rise. This prediction depends on setting up an energy balance between the heat produced, the heat lost through the lining materials, and the heat carried out the doorway. For simplicity, the room is assumed to be divided into two uniform temperature regions with the higher air temperature, T, in the upper part of the room and the ambient air temperature, T_o, in the lower part of the space. It is further assumed that there is a continuous inflow of cool air through a single open doorway into the lower portion of the room and hot air carrying gaseous combustion products exhausting from the upper part of the doorway. The mass of the pyrolysis products produced in the room is neglected. The rate of energy storage term is generally small and is neglected here. The heat balance can then be expressed as

$$\dot{Q} + \Sigma_i \dot{q}_i'' A_i = \rho CV(T-T_o) + L(T-T_o) \quad (1)$$

where $\dot{Q}$ is the total heat release rate of all the combustibles in the room exclusive of the interior finish materials, $\dot{q}_i''$ is the heat release rate per unit area of the i-th finish material, A_i is the fire involved area of the i-th finish material, ρ, C, and V are the density, heat capacity, and volumetric flow rate of the hot air and combustion products exhausting from the room, and L is the ratio of the rate of heat loss (by conduction through the linings of the room and by radiation through the doorway) to the temperature rise. This leads to the following expression for the temperature rise,

$$T - T_o = \frac{\dot{Q} + \Sigma_i \dot{q}_i'' A_i}{\rho CV + L} \quad (2)$$

When the terms in the numerator and denominator on the right hand side are all divided by the floor area, A, the set of ratios which must remain constant in order to achieve the same temperature rise in the model and prototype becomes apparent, namely, $\dot{Q}/A$, A_i/A, L/A, and V/A. $\dot{Q}/A$ is maintained constant by prescribing the strength of $\dot{Q}$, which would be the heat release rate of the gas burner used as the ignition source in the full-scale and reduced-scale tests for testing interior finish materials. A_i/A and L/A are kept constant by geometric scaling, if the fires are similar and the heat transfer coefficients are the same in full- and reduced-scale. Unfortunately, scaling of L/A is only approximate as the convective heat transfer is not scaled.

Since $V \propto WH^{3/2}$ where W is the width of the doorway and H is its height, V/A can be maintained constant by making H proportional to the scale factor and making W proportional to the square root of the scale factor. The wall above the doorway traps the hot combustion products from the fire and is critical to the phenomena taking place in the room so that this height was chosen to be scaled geometrically. For quarter scale modeling, the doorway width then is half of its full scale value while the other dimensions are only one quarter, except for the thickness of the interior finish materials.

The wall and ceiling materials must be of the same thickness as in the prototype, to insure that the heat losses per unit area remain about the same for the same interior air temperature. This is of great practical value since materials are tested in the thicknesses available in the market place and composites do not pose an additional fabrication problem.

However, the following problems are encountered with the scaling:

1. Since the lateral flame spread rate does not change with scale, it is relatively too high in the model.

2. The flame heights are too high in the model.

3. The convective heat transfer coefficient is too low in the model since air velocities are proportional to the square root of the scale.

4. Radiation from the upper walls, ceiling, and hot air layer is scale dependent when the hot air layer is semi-transparent and a vertical temperature gradient exists.

5. The increased size of the doorway opening required to scale the volumetric air flow rate permits slightly greater heat losses and slightly less heat release from combustible walls.

1.3 Objectives and Approach

The principal goal of this study was to help develop a quarter-scale room fire test for evaluating the potential fire hazard of interior finish materials. The approach was to modify the existing NBS quarter-scale working model [7], even at the risk of deviating from previously existing scaling theory, such that the maximum temperatures reached and the times to flashover and flameover* duplicate full scale tests closely enough for screening purposes and for studying the fire buildup phenomena on a much more economical scale. Two kinds of modifications were considered. One was to adjust the intensity of the heat source in the

*Flashover is defined here as the room fire condition where the thermal radiation level becomes high enough to spontaneously ignite light combustible materials, such as newspaper, in the lower part of the room. Flameover is defined as the room fire condition where flames emerge from the doorway.

model, which deviates from scaling theory. The other modification involved an empirical adjustment of the doorway opening, which does not violate scaling theory, as long as the quantity $WH^{3/2}$ remains constant. Changing the doorway in this manner would, however, affect the temperature distribution and radiative environment in the model. Three significantly different materials, fibrous glass, nitrile foam rubber, and plywood, were employed in this investigation.

Secondary objectives were to determine the effects of heating rate and location of heat release in the room on room flashover. This information is essential for determining the size and placement of an ignition source which should be sufficiently large to realistically appraise the fire hazard potential of materials and, at the same time, would not be so large as to overwhelm the material being evaluated.

2. EXPERIMENTAL TESTS

Several full-scale room fire tests, where the walls and ceiling were lined with nitrile foam rubber [8] and where the walls and ceiling were lined with plywood paneling [9], were selected as prototype tests for this modeling study. In addition, full-scale fire tests were performed with fibrous glass insulation fully covering the walls and ceiling to provide further tests for modeling. These three interior finish materials are described in table 1. The room used to test the foam and fibrous glass had dimensions of 3.0 x 3.0 x 2.3 m high and a 0.73 x 1.93-m high doorway offset to one side, figure 1. Since this room was used for a

study on fires in shipboard compartments, all four walls and the ceiling had 6.4 mm thick aluminum alloy plating mounted on 51 x 102 mm steel studs 0.41 m apart. The floor was covered with 3.2 mm thick aluminum sheet. The test material was mounted directly on the room walls and ceiling using an adhesive for the foam and screws with end washers for the fibrous glass. The corresponding model test enclosure was a one-quarter replica of this room except for the doorway dimensions and is shown in figure 2. The test room with the plywood paneling was 3.0 x 3.0 x 2.4 m high with a 0.76 x 2.03-m high doorway. This room had concrete block walls and a gypsum board-wood frame ceiling construction. Wood studs, 25 x 75 mm, spaced at 0.41 m were used as spacers between the plywood and the concrete walls and gypsum board ceiling. The model version of this room used an enclosure lined with gypsum board. Wood stud spacers and the plywood were then applied over this surface. In both model enclosures three doorway lintel depths of one-quarter, 1.4 times one-quarter and 1.8 times one-quarter of the full-scale lintel depth, labeled as lintels I, II, and III, respectively, were arbitrarily chosen to evaluate the effect of doorway height. The dimensions for these three openings are shown in table 2. Both full-scale and model room fires were conducted within a large test building so that the effects of wind and temperature extremes were minimized.

Location of all instrumentation in both size rooms is indicated in figure 1. Measurements made in many of the tests to characterize the thermal environment in the room included vertical temperature profiles down from the ceiling and along the centerline of the doorway, vertical

distribution of air flow velocities in the doorway, thermal flux to the ceiling and two walls, and radiation incident on the floor. Temperatures were measured with thermocouples fabricated from 0.25 mm diameter chromel and alumel wires. Ceiling and wall fluxes and the thermal radiation incident on the lower part of the room were monitored with water-cooled Gardon type of total heat flux gauges. Crumpled newspaper on the floor was also used as flashover indicators to show when the irradiance from the heated air and upper room surfaces was sufficient to ignite light combustible materials in the lower portion of the room. Pitot tubes were located in the upper one-third and lowest one-third of the doorway height in the large room. Bidirectional velocity probes [10] were employed in the middle one-third of the doorway opening. These bi-directional probes have the capability for measuring the velocity and the occurrence of any flow reversal along the doorway. They were used to monitor the entire height of the opening in the model.

In the tests with the nitrile foam rubber [8], a 0.305 x 0.305 m porous plate diffusion flame burner, positioned 0.305 m above the floor and in contact with both walls of one back corner of the room, served as the fire exposure source in the full-scale tests. The burner used methane gas and operated at steady heat release rates of 62 kW (for three tests) and 94 kW (for one test). The full-scale room fire tests of the plywood paneling used the same burner in the same location but with a constant rate of 90 kW. The fire source in the model was a 76 x 76 mm porous plate burner standing 76 mm high above the floor. The full-scale tests and their corresponding model tests are outlined in table 3. For

the experiments using the fibrous glass material, eighteen fire tests were conducted in the model, and six fire tests were performed in the full-scale room. Conditions for these tests are outlined on table 4. Several steady rates of heat release were employed using the above mentioned full-scale and model burners. Those rates ranged from a heat output of 62 kW, which is smaller than that from the burning of some small upholstered chairs, in the large room to rates which were sufficient to produce flashover of the space. Propane was used for the first five large scale tests shown in table 4. Test P5 was run at the highest flow possible with the 100 psi propane. A switch to bottled methane was then made in P12 to obtain a sufficient rate of heat release to cause flashover. In these tests with the fibrous glass insulation, the relationship between the rate of heat release in the room and the time to achieve flashover was also explored. As the heat release contribution from the fibrous glass was difficult to predict, it was decided to first burn away the combustible content of this insulation and then rely on the burner for the sole source of heating in the actual testing. Moderate size natural and propane gas fires were conducted for 900 s in the model and large rooms, respectively, several hours before actual testing to burn off any organic binder that might be present in the fibrous glass lining the rooms. Natural gas was used for the first six model tests. Inadequate gas line pressure forced a switch to propane fires. Tests were then run, using a propane and methane gas fire, respectively, with the same rate of heat release as in test M2I to check whether any difference would occur in the fire environment when a propane or methane fire was

used. Little difference, i.e., less than 5 percent variation, was observed in the burner flame heights, room temperature profiles and flux levels in the enclosure with the three gaseous fuels.

3. RESULTS AND DISCUSSION

3.1 Model Simulation of Room Fires

3.1.1 Nitrile Foam Rubber Insulation

Doorway and interior air temperatures and flashover times for the four full-scale tests and their corresponding model tests are presented in table 3 [8]. Flashover was assumed to have occurred at a time taken to be the average of the times for the first two indicators (newspapers) to ignite. Ignition of the newspaper, a specified flux level at some location on the floor, or some designated minimum doorway or interior air temperature can all be used to indicate the onset of flashover. However, there are problems associated with the use of each method. Variation in the thermal and physical properties of newspaper can result in the newspaper igniting over a range of fluxes between 17 and 25 kW/m^2 [11]. Non-uniform distribution of thermal fluxes throughout the room also poses a problem for determining flashover with both flux meters and newspaper flashover indicators. Non-uniform distribution of temperatures throughout the room and thermal radiation errors associated with thermocouple measurement of temperature affect the accuracy of interior and doorway

air temperature measurements. All of the above techniques for determining flashover can, however, help support each other. Moreover, where an ignition of the newsprint indicator had occurred, room and doorway temperatures either had attained or continued to increase to at least 650°C and 550°C, respectively. The latter temperature levels are above those usually prescribed for the onset of flashover.

The full-scale tests FS-1, FS-2, and FS-3 all attained flashover within the test period of 600 s. However, only one of the corresponding tests with the model having the lintel I doorway (test 6) reached flashover. Tests 4 and 10 reached peak doorway temperatures of 215°C or less. When the doorway height was lowered by 7 percent, as was the case with the lintel II opening, two of the three model tests, numbers 22 and 23, attained flashover. However, in test 24 which was the counterpart of test FS-3, the temperatures in the doorway peaked at only 288°C. Lowering the doorway further to 14 percent as in test 34, corresponding to the lintel III model version of test FS-3, resulted in flashover. In general, whenever flashover occurred in the model, it developed slower than in the corresponding full-scale test. For the full-scale test FS-4, the peak doorway temperature was about 300°C. Lowering the lintel from II to III in the model did not increase model doorway temperatures much beyond what may be regarded as experimental variation expected between similar tests. Again, the model fire developed slower, but the peak fire buildup, as evidenced by the maximum air temperature in the doorway, simulated the full-scale behavior. Figure 3 shows the doorway air temperature variation with time for the model tests having the lintel III doorway and for their

counterpart full size fires. A condensed version of table 3, showing a comparison of the fire buildup in the full- and quarter-scale compartment fires of the nitrile foam rubber, is given in table 5.

Flux measurements at the time of flashover for the full-scale and corresponding quarter-scale tests are indicated in table 6. The average irradiance on the floor at which flashover occurred was 22 kW/m^2 for the full-scale fires FS-1, FS-2, and FS-3, and 24 kW/m^2 for the model fires 23, 33, and 34. The irradiance level on the floor for test FS-4 was also lower than that for its counterpart model test. This was also observed in tests where the interior finish was an inert fibrous glass insulation (refer to section 3.1.3). The higher flux probably resulted from the relatively taller burner flames in the model and from the relatively larger heated surface area in the model which occurred as a consequence of the lowered lintel.

The vertical air temperature profiles inside the room and along the doorway for three full-scale fires, at their respective times of peak air temperature as measured at a location 102 mm below the doorway lintel, are shown in figures 4 and 5. Superimposed on the figures are the corresponding test data from the model tests 33, 34, and 51 with the lintel III doorway. The times to reach the peak doorway air temperature for tests FS-2, 33, and 34 also corresponded to the times for flashover, whereas flashover occurred seconds after the peak doorway air temperature was attained in test FS-3. In the model tests 33 and 34, temperatures were lower than in the full-scale test and, consequently, the model fires

required a longer fire exposure of the insulation in order to reach flashover. For model test 51 and its corresponding full-scale fire FS-4, the fire was confined principally to the zone in contact with the flames from the ignition source, producing only a moderate air temperature rise. The vertical distribution of temperatures below the center of the ceiling indicated much higher temperatures in the model than those in the full-scale fire. However, these temperature differences in the upper part of the compartment did not show up in the doorway temperature profiles. This may be explained by the relatively taller flame heights in the model. The higher flames could have resulted in a more intense localized heating of the thermocouples in the upper region of the compartment. However, the heated air in the compartment space became well stirred by the time it reached the doorway. This is evident from the similarity in the doorway temperature profiles for the two tests.

Repeatability of these model tests and the feasibility of adjusting the intensity of the ignition source to achieve satisfactory modeling were also studied with the results indicated in table 7. Tests 5 and 17 were repeat tests of tests 4 and 16, respectively, and show good repeatability between tests in the doorway air temperatures but less agreement in the interior temperatures. Tests 16 and 17 showed that an increase in the heat release rate of the ignition source by as much as 50 percent can sometimes have little effect on room fire buildup. For the C2 insulation used in that test, the lowering of the doorway by 7 percent as in test 22 had a much greater effect on the fire growth than a significant increase in the size of the fire initiation source. For the B2 insulation, a

50 percent increase in the intensity of the ignition source led to flashover, but test 34 demonstrated that small decreases in doorway height could also lead to equally large increases in room interior and doorway air temperatures.

3.1.2 Plywood Paneling

Data from the two full scale room fire tests and the corresponding model tests 1 and 2, conducted in a previous study [9], are outlined in table 3. Data from model tests 3, 4 and 5, which were performed for this present study, have been included in table 3. Model tests 1 and 2 used a doorway height which was 0.90 as high as the quarter-scaled doorway. Model test 3 used a quarter-scaled doorway while tests 4 and 5 had doorway heights 0.93 and 0.86 as high, respectively, as that in test 3. The plywood used for all of these tests appeared to be of the same material. However, full-scale test 1 did not reach flashover, while full-scale test 2 conducted one week later experienced flashover in 158 s. Model test 1, conducted immediately after the full-scale test 1, also did not reach flashover, while model test 2, performed in the same day as was full-scale test 2, had one of its newspaper flashover indicators ignite at 185 s. Figure 6 shows good agreement in the chronological development of the fire between model test 2 and its counterpart full-scale fire test 2. Model tests 3, 4, and 5 were conducted over the range of relative humidities from 35 to 45 percent. Room flashover times for these three tests occurred between 310 and 350 s. The different degree of fire buildup between the full scale tests 1 and 2 and the differences among model

tests 1, 2, and the last three model tests could be ascribed to a combination of varying properties for the plywood paneling and to differences in humidity conditions during each test.

Unfortunately, humidity conditions were unknown for the full-scale tests and for the model tests 1 and 2, and no more of the same paneling was available for a study on the effect of humidity on room fire growth using this material. A substitute plywood paneling was employed for this latter purpose. This plywood was tested in the model having a 14 percent lowered doorway opening under several humidity conditions. The data shown in figure 7 indicated that the times required to reach flashover varied randomly between 223 and 323 s over the range of relative humidities from 22 to 76 percent. Evidently, the variation in material properties and its effect on the room fire development overwhelmed the differences due to humidity. It is possible that the plywood used in the full-scale tests and in the model tests 1 to 5 was more sensitive to humidity and, thus, could have accounted for the differences between tests shown in table 3. On the other hand, different batches of the plywood paneling having different material properties could have been used for each of the following sets of tests: (1) full-scale test 1 and model test 1, (2) full-scale test 2 and model test 2, and (3) model tests 3, 4, and 5. Care was taken to assure that material from a single batch was used in the last three model tests and that these tests were performed under a narrow range of humidity conditions. Results in table 3 showed that only small differences occurred as a consequence of modifying the height of the doorway when this plywood material was used. This was

believed to be the result of rapid flame development over the surfaces of the wall and ceiling materials.

3.1.3 Fibrous Glass Insulation

Results of the fire tests M2I, M2II, and M2III in the quarter-size models having the geometrically scaled, 7 percent and 14 percent lowered doorway heights, respectively, are compared with the data from the corresponding full-size room fire test P2 in figures 8, 9, 10, 11, and 12 and in table 4. Temperature histories near and on the ceiling for these tests are shown in figures 8 and 9. Vertical temperature profiles inside the room and at the doorway opening are presented in figures 10 and 11. These temperature histories and profiles show that the model having the geometrically scaled doorway height gives a better simulation of the temperatures in the full-scale room fire.

Air flow velocities along the centerline of the doorway opening are indicated in figure 12. The three models have about the same velocity distribution along the height of the doorway. Doorway flow velocities for all of the fire tests on the fibrous glass insulation are given in table 9. The scaling criteria suggest that velocity should scale as the square root of the scale factor, meaning that the full-scale values should be twice as large as the model velocities. Inspection of the test data indicates that this is roughly the case. The calculated volumetric flow rate determined from these profiles was uncertain by as much as 30 percent as the calculated outflow was about 20 to 30 percent larger

than the calculated inflow. There is evidence that volumetric flow rates calculated from just centerline velocities could give outflow rates which are 20 to 30 percent higher than the calculated inflow rates, and that this apparent excess outflow results from an insufficient mapping of the flow across the entire doorway area [12,13]. Nevertheless, the agreement between the temperature profiles between M2I and P2 suggested that the volumetric inflow rates to the model room properly scaled the inflow to the full-scale fire.

Although geometric scaling of the doorway height leads to adequate reproduction of the temperature profiles, provided the rate of heat production is properly scaled, the heat fluxes to the room surface are not scaled properly. This is due to: (1) the flame height being relatively higher in the model, (2) the velocity of the flow of hot air and combustion gases in the model room being lower, and (3) the thickness of the layer of hot air and combustion gases being less in the model. A greater flame impingement area from the burner in the model results in a larger area of high surface temperature. This results in a general increase in thermal radiation levels in the room. On the other hand, the convective and radiative heat transfer from the hot air and combustion gases to the model room surfaces would be lower as these quantities decrease with decreasing velocity and decreasing thickness of this hot layer, respectively. Convective heating is the dominant mode of heat transfer near and within the flame zone, which extends upwards from the ignition source. With combustible materials, the flame spread away from this zone would be slower in the model. This has been the case with the

fires discussed in sections 3.1.1 and 3.1.2 where the times to attain room flashover were slower in the model than those for the full-scale fires. For the fibrous glass insulation, which did not contribute to the fire, thermal flux measurements for tests M2I, M2II, M2III, and P2 (presented in table 8) indicate that the total heat flux measured at the heat flux meter locations was greater in the model fires that in the full-size counterpart test. The data indicate that the heat flux values along the walls and on the floor were highest in the model with the lintel III doorway. This results from a thicker heated layer of air and combustion gases and more surface exposed to the elevated temperature caused by the lowering of the doorway in the model.

The effect of lowering the doorway in the model on fire buildup was also investigated for the case where the heating rate from the gas burner was raised sufficiently for rapid flashover of the room. Results of the model fire tests M12I, M12II, and M12III, having the lintel I, II and III openings corresponding to the geometrically scaled, 7 percent, and 14 percent lowered doorway heights, respectively, are compared with data from prototype test P12 in tables 4 and 8. When the burner heating rate was raised sufficiently for rapid flashover in the model and full-scale room fires, flames covered much of the ceiling in both cases and the relative areas covered by the flames did not differ appreciably between the model and full-scale tests. However, the layer of heated air and combustion gases was thicker in the full-scale fire than was the hot layer in the model fire which led to a more intense radiative environment in the full-scale room. The data showed that the gap in the flashover

times resulting from these differences in the model and full-scale fires could be bridged considerably by lowering the doorway, which consequently increased the thickness of the layer of hot air and combustion gases in the model. The time required to reach flashover decreased from 138 to 90 s as the doorway opening was lowered from the lintel I to the lintel III height. The flashover time of 90 s for the model with the lintel III opening compared well with the time of 78 s required for flashover in its counterpart full-scale test P12.

In many of the tests, the incident thermal flux value on the floor at the time of flashover was lower than the 17 to 25 kW/m^2 range expected to ignite the newspaper flashover indicators. A simple experiment was performed to observe the effect of room flux distribution on the ignition times of crumpled newspaper under one room flashover condition. The same full-scale test room with the fibrous glass lining and corner gas burner was used. The floor of the test room was divided into nine equal sections with a piece of crumpled newspaper placed in the center of each section. A heat release rate of about 500 kW was used for the burner. Ignition times for the newspaper flashover indicators were recorded and are given in figure 13. The results showed newspaper ignition times varying between 39 and 92 s, with the longest times occurring at the three corners farthest from the burner. Figure 13 also indicated that the placement of the floor flux meter for the tests in table 8 was at a position where the flux was too low, resulting in values significantly lower than the 17 to 25 kW/m^2 range anticipated at the time of flashover.

3.1.4 Other Materials

Several other materials have been evaluated with both the model having the 14 percent lowered doorway and full-scale room fire testing in a separate study [9]. In that study, three types of polyurethane, a foil-faced and an unfaced polyisocyanurate, fiberboard, and unfaced fibrous glass were used. Further description of these materials along with some of the test results from that study are outlined in table 10. Included in table 10 is a summary of the room flameover and flashover times for all of the tests with the nitrile foam rubber, plywood paneling, and fibrous glass insulation where there were both full-scale and quarter-scale counterpart tests. The results indicated that materials which resulted in rapid flashover in the full-scale tests also did so in the model tests; while those materials which did not contribute significantly to the full-scale room fire development also did not contribute much to the model room fire growth. In general, fire buildup times (e.g., times to reach flameover and flashover), took longer in the model, and this can be seen in the data for the three polyurethanes. This could result in situations where the fire development just barely reaches flameover and/or flashover conditions in the full scale test, but would not do so in the model test. This situation is well illustrated with the polyisocyanurate test where the time to reach flashover was 368 s and no flashover happened in the corresponding model test. However, in borderline flameover or flashover situations such as this, other indicators such as the interior and doorway air temperatures in the model could be used instead to help predict full scale behavior.

3.2 Fire Location and Fire Buildup

Three different burner positions along the floor were considered in the room fire tests to help assess the effect of burner location on fire buildup and as a further check on the model's ability to follow the full-scale fire development. These locations, as indicated in figure 1, were at a back corner, the center of the back wall, and the center of the floor. The effect of placement of the fire source on the temperature and the flux levels in the room and on the temperatures and flow velocities along the doorway opening for both the model and full-scale fires are given in figures 14-19 and in tables 4 and 8. The figures show that as the burner was moved from the floor center to the back wall, and from there to the corner of the room, the heated air in the room and the hot exhaust through the doorway became more and more concentrated in the upper regions of the room and near the top of the doorway. In general, the model fires behaved much like the full-scale tests except for somewhat higher air temperatures resulting from the lowered doorway in the model. The flow through the doorway did not change appreciably when the burner was relocated from the back wall to the corner. Thermal flux levels for the three burner locations in both of the quarter- and full-size fires are presented in table 8. Ceiling fluxes for the corner burner placement were higher than those for the fire source positioned against the back wall. This resulted from the longer flames when the fire was in the corner. The shortest flames occurred when the burner was at the room center. However, at the latter location the flame was directly under the flux meter and, consequently, the instrument saw a higher flux

than when the fire was placed at the back wall. Thermal fluxes, in general, were lower for the full-scale fires. This was a direct consequence of the relatively shorter flames in the full-size tests.

The highest ceiling temperature and air temperatures in the room and at the doorway occurred when the burner was used in the corner as in test M2II instead of being used against the back wall or at the center of the floor as in tests M3II and M4II, respectively. Locating the burner or another fire initiation source at the center of the floor is not suitable as the flames from any reasonable size fire can not directly contact the wall material. Placement of the ignition source against the back wall or in the corner are two practical alternatives. Corner placement of the burner or another fire initiation source appears to be more desirable as the room interior finish would be evaluated under the more demanding but yet realistic fire exposure for any given rate of heat release for the ignition source.

3.3 Heat Production Rate and Fire Buildup

A wide range of heat release rates in the room fire tests was employed to determine combinations of heating rates and exposure times required for room flashover and to check the performance of the model under conditions of modest heating all the way up to flashover. Table 4 arranges the various quarter- and full-size fire tests in the order of increasing rates of heat generation in the room. Figures 20-22 show the temperature buildup near the ceiling, on the ceiling, and along the top

of the doorway opening for corner placement of the fire source in the model and full-scale tests. For the two lower heating rates shown, the model tests M1II and M2II or M2III exhibited higher air and surface temperatures than those in the full size tests P1 and P2. This was expected as a consequence of the lowered doorway height in the quarter size enclosure. For model tests M1II and M2II the ceiling flux was also higher than that in their corresponding tests P1 and P2 due to the taller flames in the model fires. However, at the full-scale equivalent heating rate of 460 kW, the temperatures in test P12 exceeded those for the corresponding model test M12II or M12III. Table 8 indicates that at the latter heating rate the ceiling flux level in the full-scale fire was also higher than that in the counterpart model test at their respective times of flashover. There are two explanations as to why air temperatures and the ceiling flux were higher in this full-scale test. The first reason is that the ceiling in both P12 and M12II or M12III were fully covered by the burner flames, meaning that the longer flame in the model merely spills over and out of the opening and would not contribute significantly more to the fire. Secondly, the higher convective heating and thicker hot layer of air and combustion gases in the full-scale fire apparently overshadowed the additional trapping of heat in the room when the lowered lintel height was used in the corresponding model test, resulting in higher ceiling flux and higher air temperatures in the full-scale room.

The degree of flame coverage of the ceiling plays a dominant role in the determination of the thermal flux environment in the fire room. The

full-size test P5 was conducted with a 50 percent higher scaled rate of heat release than those in the model tests M2II and M2III, but it did have the same degree of flame coverage of the ceiling as those in the two small-scale fires. Except for the wall fluxes in test M2II, the flux measurements in table 8 indicate that the flux levels at the floor, wall, and ceiling were about the same for the three tests.

Heating rates leading to flashover of the space for the three burner locations in the room are indicated in table 4. As the interior finish in the room fire experiments was an inert fibrous glass having good insulating properties, these rates of heating could represent minimum rates needed in practice. The lowest full-scale equivalent rate of heat generation found to lead to flashover in the model room was 300 kW, maintained for almost 420 s, at the corner of the room. At a heating rate of 460 kW in the corner, flashover times of 80 and 100 s were found for the full-scale and model tests, respectively. Increasing the rate to 645 kW resulted in flashover of the model room in only 45 s. When the fire source was placed against the back wall, a heating rate of 375 and 410 kW led to flashover at 240 s in test M10II and at 126 s in test M11II, respectively. With the burner at the floor center, a rate of 460 kW could not ignite the newsprint flashover indicators over an exposure time of 480 s, at which time the heating rate was increased to 494 kW. After another 45 s, the room flashed over. When a rate of 475 kW was employed with the burner at the floor center, flashover occurred in 138 s.

Other flashover experiments have also been conducted in reduced-scale models [14,15]. Fire tests in a similar sized quarter-size enclosure lined with gypsum board [14] demonstrated that a full-scale equivalent rate of heat production of 670 kW, maintained over a 300 s period, at the floor center, could result in flashover of the room. Waterman [15] performed similar experiments with an one-eighth scale model of a 3.7 x 3.7 x 2.4-m high room having an interior lining of cement-asbestos board. Instead of a doorway opening, his enclosure had a scaled down version of a 1.22 m wide and 1.37 m high window. However, the ventilation factor, $WH^{3/2}$, discussed in section 1.2, was the same as that for our model doorway. He found that about 650 kW along one side wall was needed to flashover the space. Both of these previous studies employed models lined with materials having much higher values of thermal conductivity, k, as well as thermal inertia, $k\rho c$, (the product of the thermal conductivity, density, and heat capacity of the material). The thermal inertia of a material determines the rate of the temperature rise of a surface exposed to the fire. If the thermal inertia is low, the surface temperature then rises rapidly, and the irradiance from the heated surfaces increases even faster. Thermal conductivity, on the other hand, determines the ultimate extent of the temperature rise. Gypsum and asbestos boards have k values of about 0.17 and 0.11 W/mC, respectively, as compared with 0.035 W/mC for fibrous glass. Furthermore, the room which was lined with the cement asbestos board also had a 40 percent greater interior surface area for thermal losses. Consequently, the heating rates for room flashover in those studies were considerably higher than the rates found with exclosures which were lined with the fibrous glass.

In general, the heat release rate needed for room flashover depends on room construction and configuration; the type, quantity, and distribution of combustible materials or fuel; and, on the ventilation conditions. Neglect of one or more of these factors could lead to serious error in predicting the potential of a room for flashover. For example, one such simplification method assumes that only the fuel heat release rate, $\dot{q}$, and the available air supply expressed in terms of the room ventilation factor $WH^{3/2}$ may be adequate for estimating the room flashover potential [16]. The expression derived in that study can be given as

$$\dot{q} \simeq 600 \ WH^{3/2} \ (kW)$$

where $WH^{3/2}$ is in units of $m^{5/2}$. In the present test series with the fibrous glass lining, a ventilation factor of 0.123 $m^{5/2}$ was used in the quarter-scale tests. Using the above formula, this ventilation factor corresponded to 73 kW, which when multiplied by the scaling factor of 16, corresponded to a full-scale counterpart of 1170 kW. However, the results outlined in table 4 showed that a rate of heat release of only 300 kW would be required for flashover of the room. In all practicality, this 300 kW represented a minimum value needed for flashover in the fire test room. For more typical room lining materials having a higher thermal inertia, the heat release rates needed for flashover would be higher. For room fires involving combustible interior finish and furnishings, instead of just the methane or propane fuel source, the flames and combustion products would have a higher optical density. The latter could help obscure radiation from the heated room surfaces and, hence, also result in

requiring a higher rate of heat release for flashover. Nevertheless, even though the simplified formula was satisfactory for many situations, it was entirely inadequate for the room fire tests performed here.

A procedure, which takes into account the physical properties of the interior finish, room size, and doorway openings, is also available for estimating room temperature as a function of heat production rate [17]. This method assumes that the room is at a uniform temperature, e.g., equal to the air temperature measured near the ceiling, and that the thermal loss per unit surface area is uniform over the entire surface of the room, including the floor and door areas. The expression given in that study is as follows:

$$\dot{q} = \left\{\sqrt{g}\, c_p \rho_o T_o^2 \left(\frac{\Delta T}{480}\right)^3\right\}^{1/2} \cdot \left\{h A_w A_o \sqrt{H_o}\right\}^{1/2}$$

where the heat transfer coefficient h is given as

$$h = \sqrt{\frac{\rho c k}{t}}$$

and where, for the case of the full-scale room lined with fibrous glass insulation,

A_o = Opening area, $W_o \times H_o$ ($1.4\ m^2$),

A_w = Effective surface area for heat transfer including door area = $2(L \times H + L \times W + H \times W)$ or ($45.6\ m^2$),

c = Specific heat of ceiling/wall material ($0.8\ kJ \cdot kg^{-1} \cdot K^{-1}$),

c_p = Specific heat of air ($1.1\ kJ \cdot kg^{-1} \cdot K^{-1}$),

g = Gravitational constant ($9.8\ m \cdot s^{-2}$),

h = Effective heat transfer coefficient through ceiling/walls ($kW \cdot m^{-2} \cdot K^{-1}$),

H = Height of room (2.3 m),

H_o = Height of room opening (1.93 m),

k = Thermal conductivity of ceiling/wall material ($0.035\ kW \cdot m^{-1} \cdot K^{-1}$),

$\dot{q}$ = Heat release rate of fire (kW),

ρ = Density of ceiling/wall material ($60\ kg \cdot m^{-3}$),

ρ_o = Ambient air density (approximately $1.2\ kg \cdot m^{-3}$),

t = Time of exposure (s),

T = Temperature (°C or K),

T_o = Ambient temperature (approximately 20°C or 293 K),

ΔT = Temperature rise relative to ambient
$= T - T_o$ (°C),

W = Width of room (3.0 m), and

W_o = Width of room opening (0.73 m).

For model test M14II in table 4, an air temperature of about 600°C was achieved at a time of 138 s. If the corresponding full-scale test

behaved in the same manner, then a fuel heat release rate, $\dot{q}$, of about 450 kW would be obtained for the test using the above procedure. This compared well with the full-scale equivalent value of 475 kW actually used. In model test M7II, an air temperature of 544°C was reached at 402 s. The calculated full-scale equivalent for this test would be 295 kW compared with the 300 kW used.

4. SUMMARY AND CONCLUSIONS

1. The interior finish materials used for this study were nitrile foam rubber, plywood paneling, and fibrous glass insulation. In addition, data from another study [9] involving polyurethane, polyisocyanurate, fiber board, and fibrous glass were used to support this work.

2. Empirical adjustment of the scaling criteria for the doorway with regard to the quarter-scale model room fire test developed at NBS resulted in closer agreement with full-scale room fire behavior. It was necessary to lower the doorway opening in the model by 14 percent to obtain flashover with the materials considered in this study and with the model equivalent of the gas burner heat release rate that produced flashover in the full-scale test. However, a theoretical basis is still needed to justify the general use of this modified doorway.

3. The modified quarter-scale model room fire test can also duplicate the peak fire buildup, as evidenced by the peak air temperatures

reached inside the room and at the doorway, in full-scale room fires not having the potential for flashover. The duplication of the full-scale test results is close enough for screening purposes.

4. The modified model test still takes longer to reach the peak fire buildup than does its counterpart full-scale test. Consequently, in situations where the fire development in the full-scale test just barely reaches flashover, the model fire may only approach flashover conditions. In these cases, other indicators such as the peak interior and doorway air temperatures in the model could be used to help predict the flashover potential of the full-scale tests.

5. Corner placement of the ignition source appears desirable as the room interior finish would be evaluated under the more demanding fire exposure location than, e.g., at the center of the floor or against the back wall, for any given rate of heat release for the ignition source.

6. A minimum heating rate of 300 kW is required to cause flashover in a 3 x 3 x 2.3 m room lined with fibrous glass and having a 0.76 x 2.03 m high doorway opening when the fire is located in one back corner of the room. The heating rate required to cause flashover would depend to some extent on the characteristics of the fire and, in most cases, be higher for other wall finish materials.

7. The severity of the ignition source in room fire experiments should be expressed in terms of some fraction of the minimum heating rate required to cause room flashover. The source should be large enough to adequately assess the fire hazard potential of materials, but should not be so large as to overwhelm the material being evaluated.

5. ACKNOWLEDGMENTS

Appreciation is expressed to Mr. Charles Veirtz, who built the test room and performed the actual testing, and to Mr. W.J. Parker for his helpful comments throughout the project.

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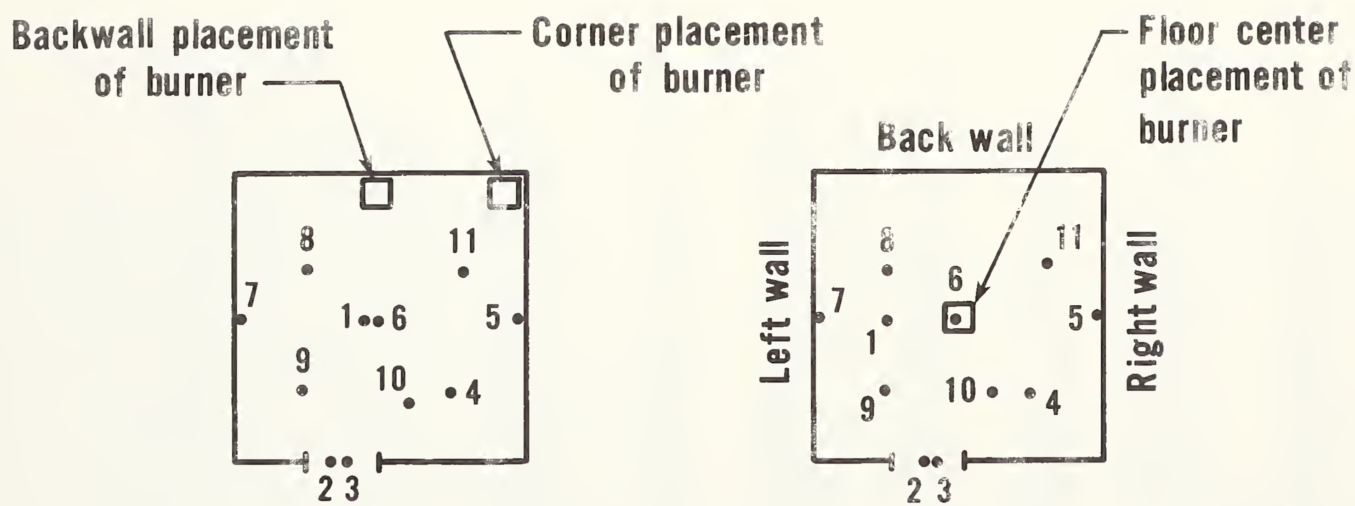

Station	Instrument
1	Vertical strand of up to 13 thermocouples extending from ceiling to floor
2	Vertical strand of up to 9 thermocouples along doorway
3	Pitot tubes along length of doorway
4	Thermal flux gauge on floor
5	Thermal flux gauge, flush with right wall surface, one-quarter of way down from ceiling
6	Thermal flux gauge, flush with ceiling
7	Thermal flux gauge, flush with left wall surface, one-quarter of way down from ceiling
8 to 11	General vicinity for flashover indicators (newspaper) on floor

Figure 1. Room arrangements showing locations of fire source and instrumentation

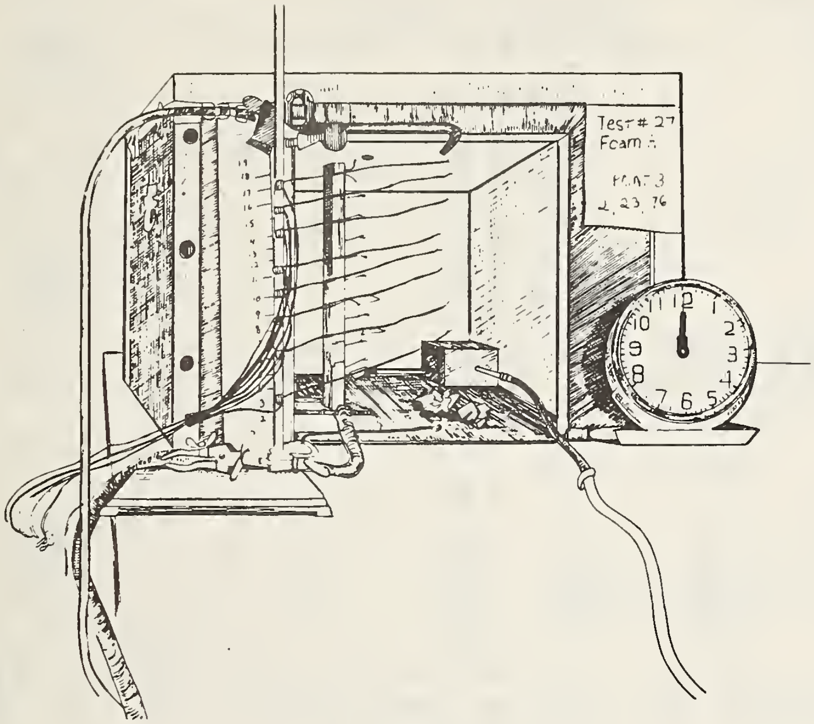

Figure 2A. Quarter-scale room fire test prior to ignition

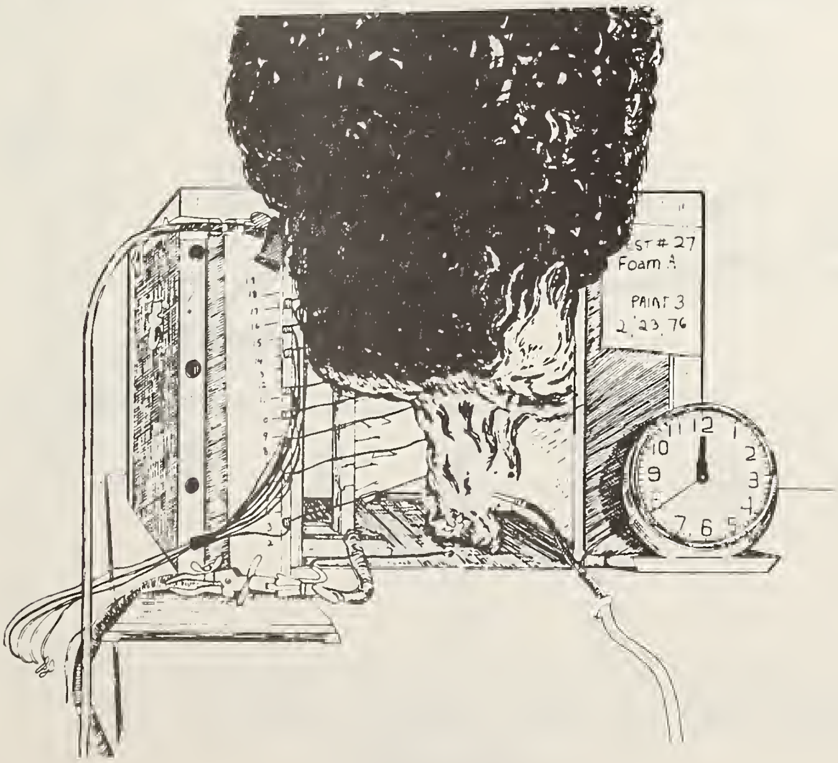

Figure 2B. Quarter-scale room fire test at flashover

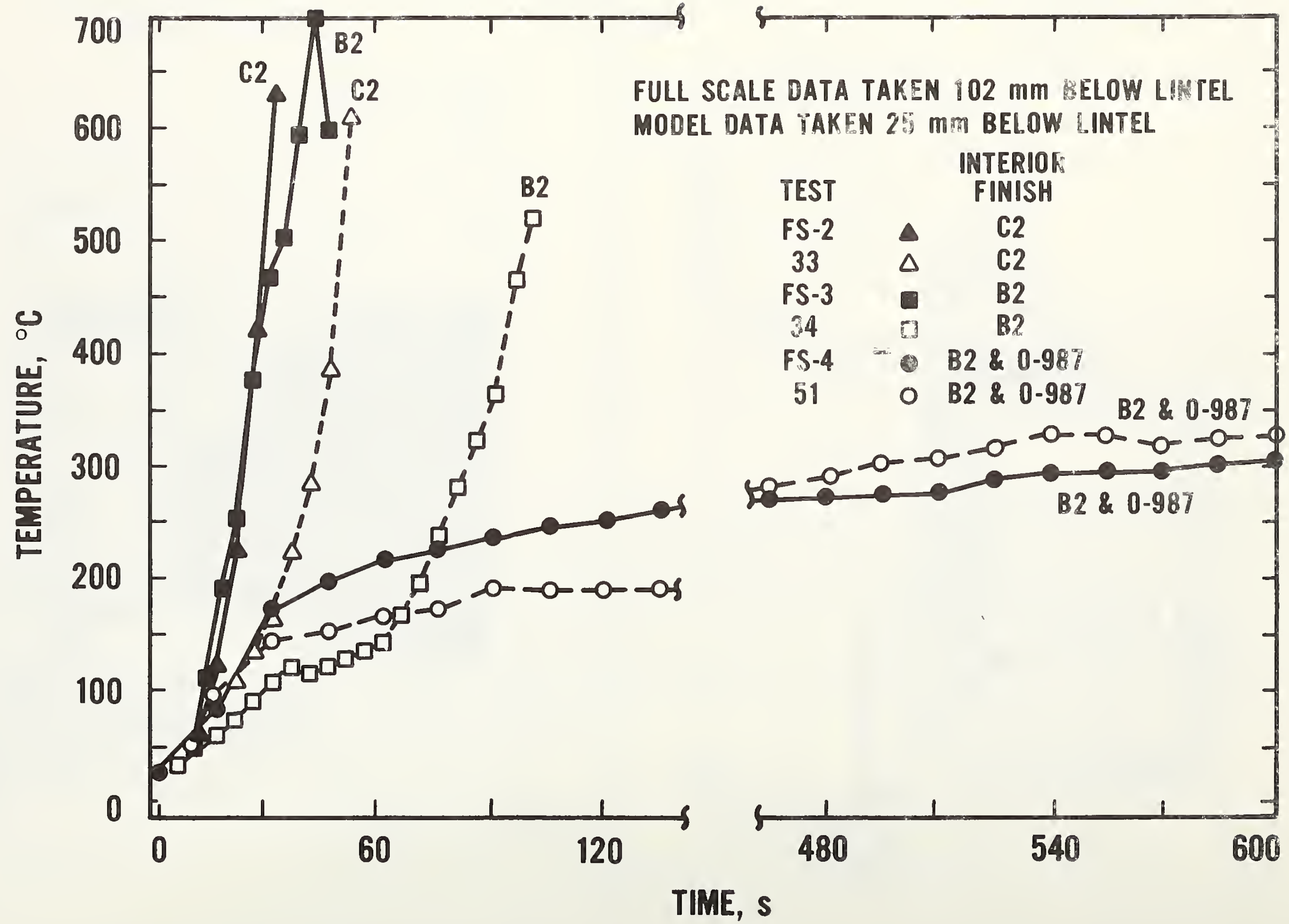

Figure 3. Top of doorway air temperature histories for several full-scale fires and model tests using lintel III

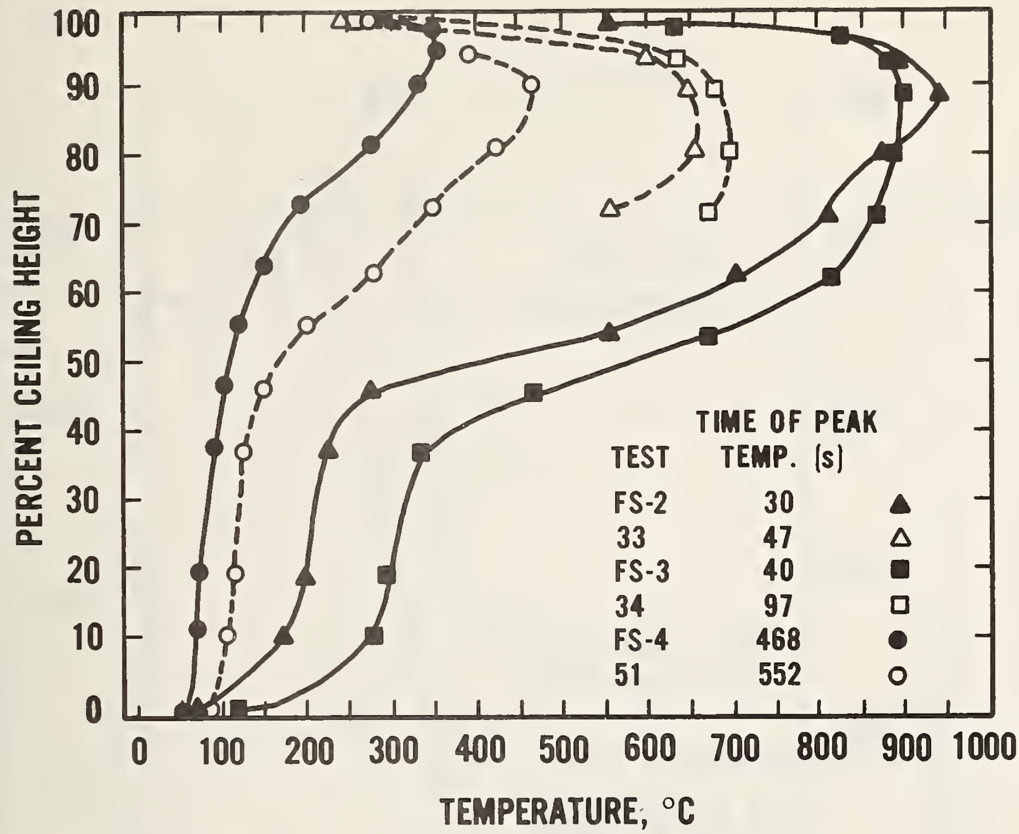

Figure 4. Room air temperature profiles at time of peak doorway air temperature

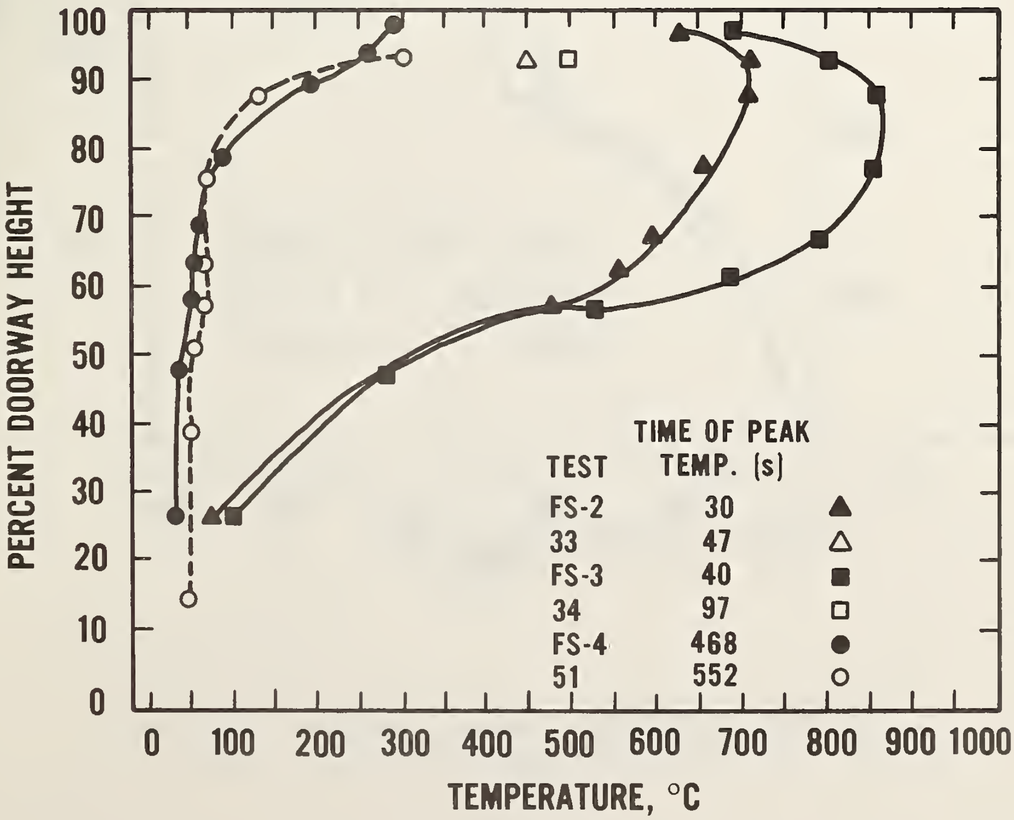

Figure 5. Doorway air temperature profiles at time of peak doorway air temperature

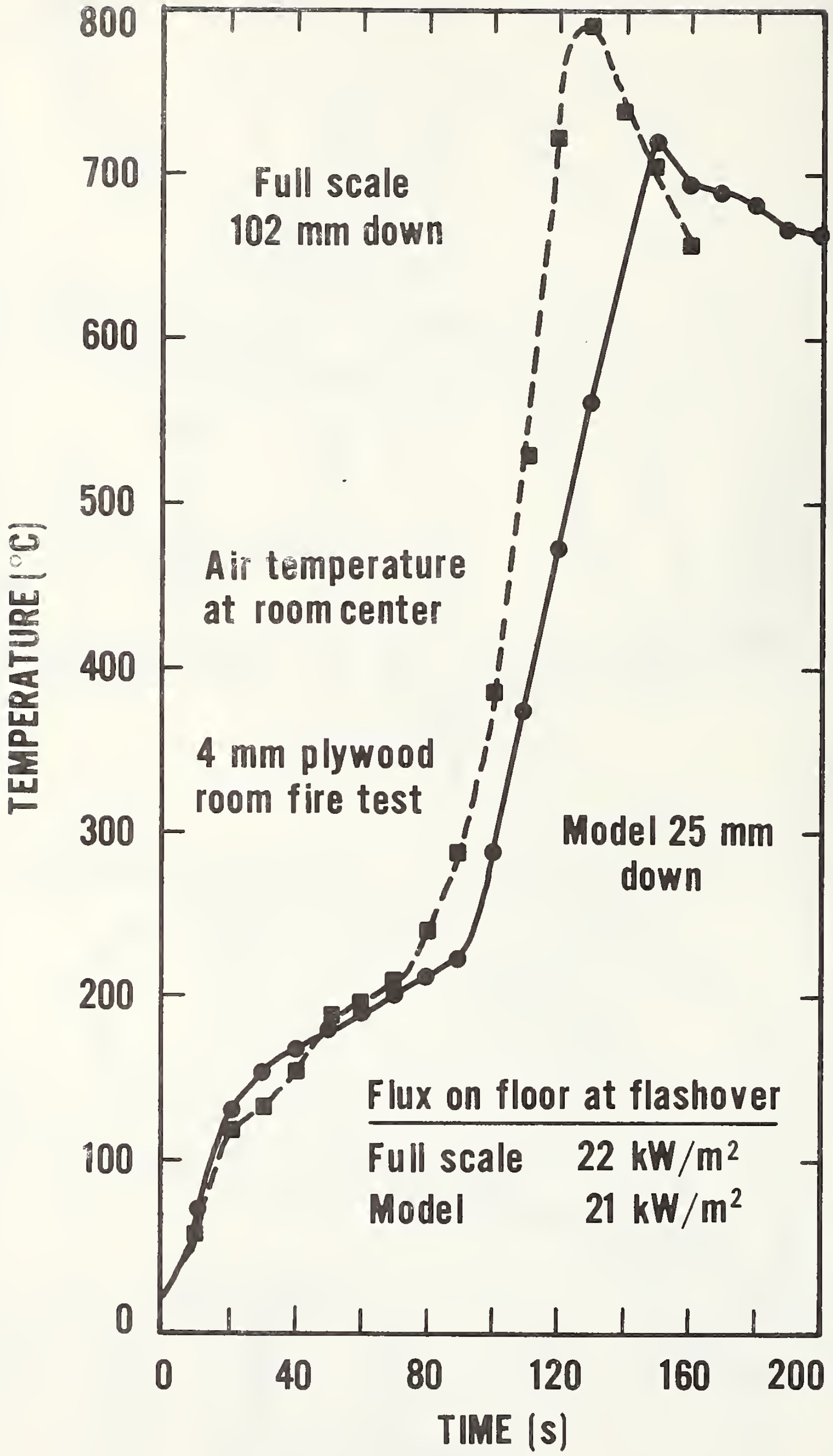

Figure 6. Comparison of full-scale and model room fire test on plywood

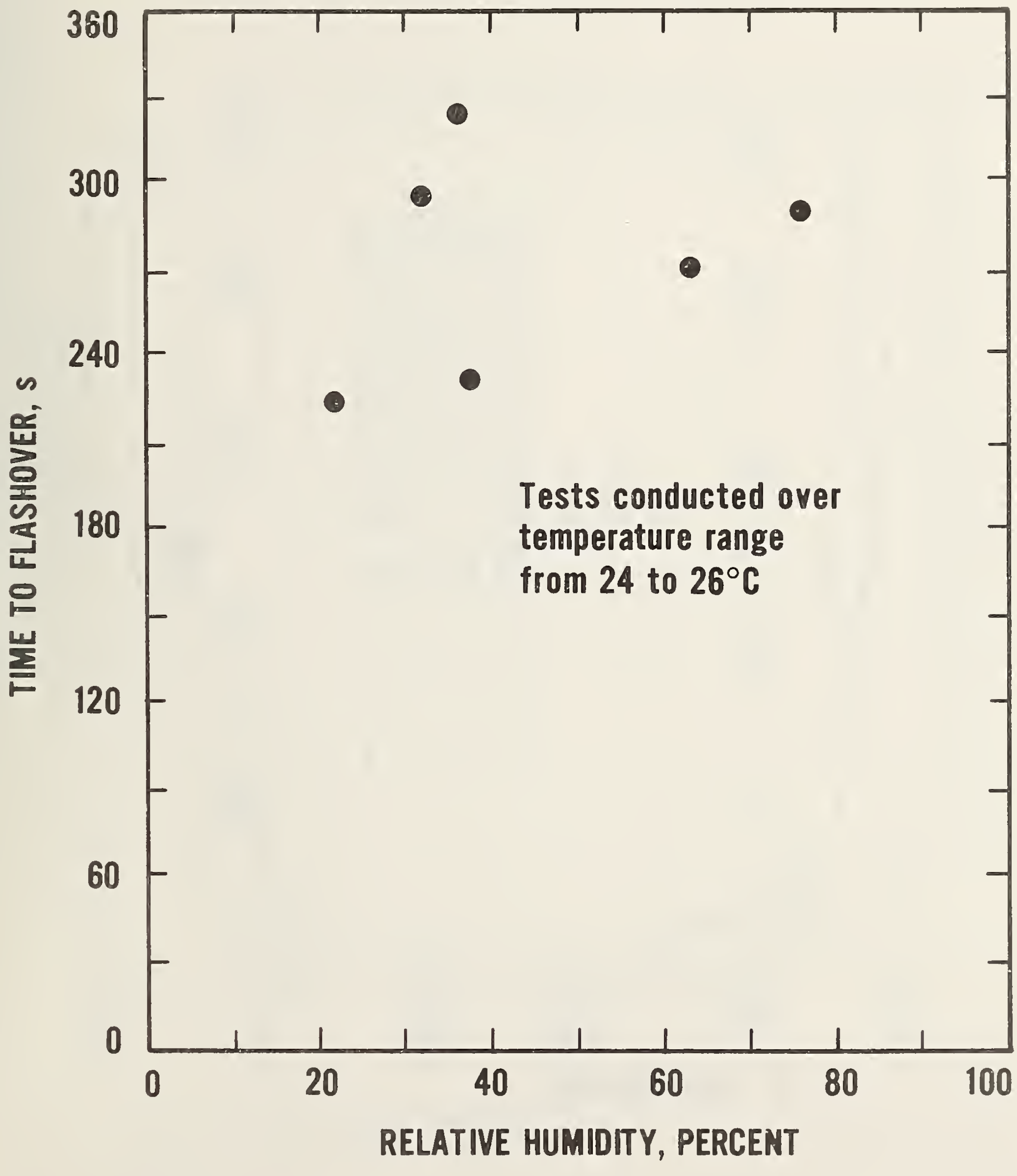

Figure 7. Flashover time versus relative humidity for model room fire tests with plywood paneling

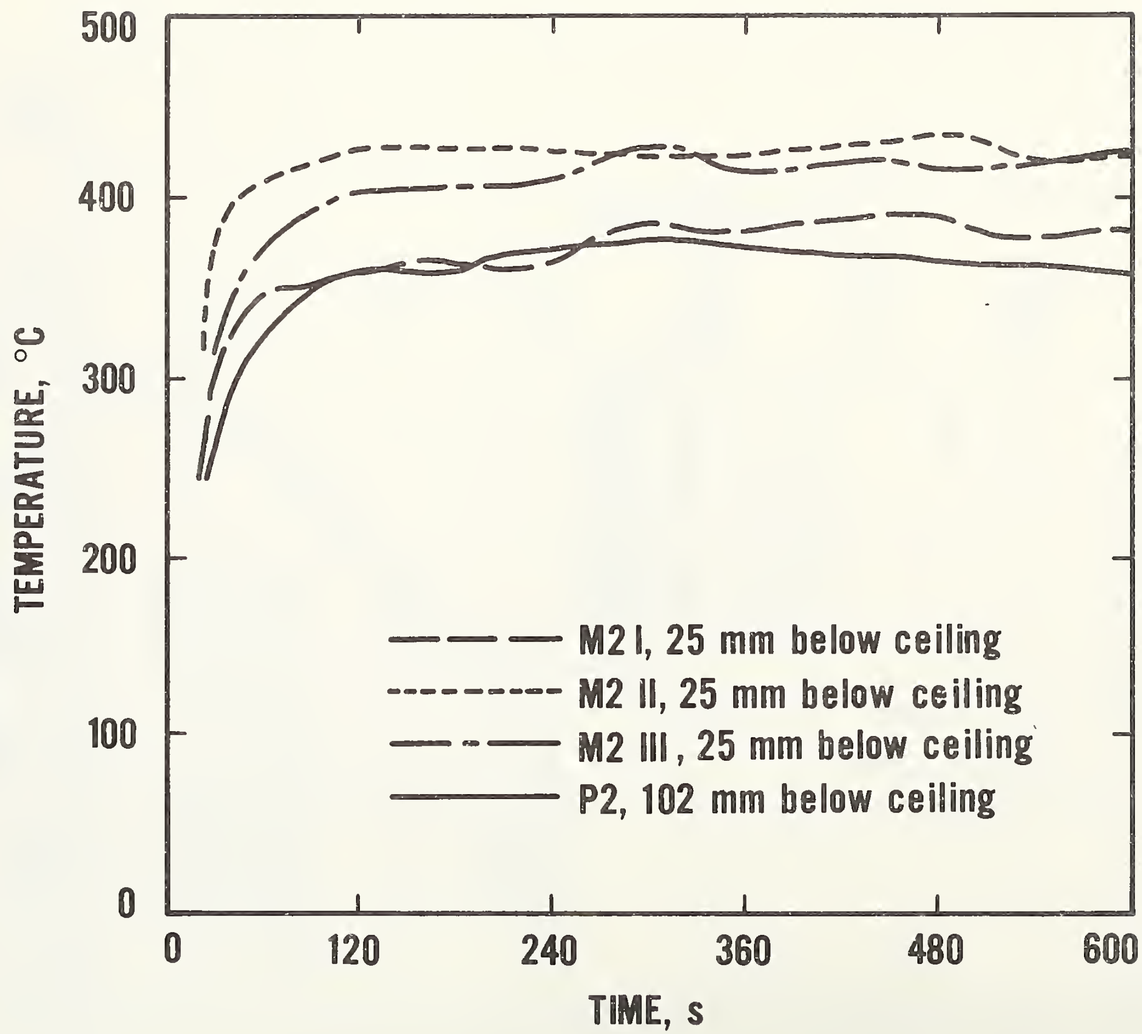

Figure 8. Room air temperature histories for full-scale fire P2 and model fires M2I, M2II, and M2III

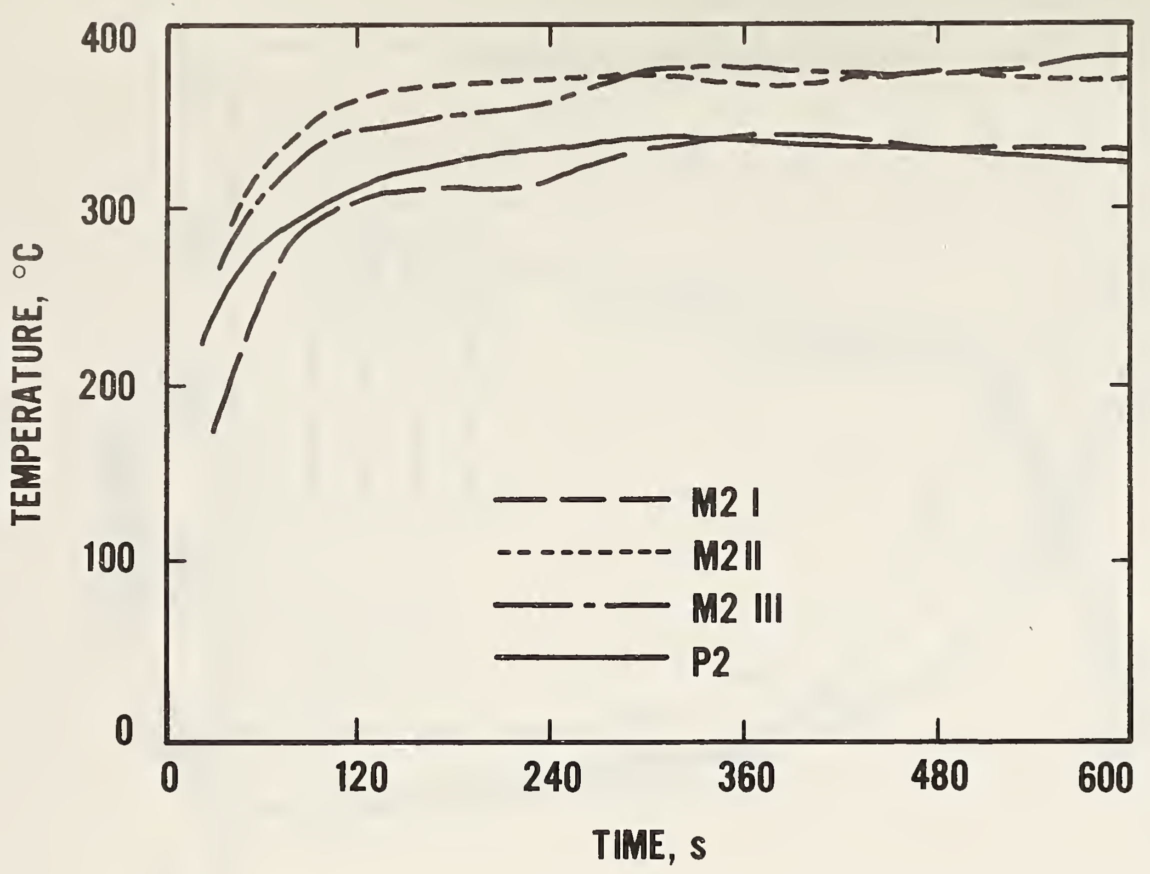

Figure 9. Ceiling temperature histories for full-scale fire P2 and model fires M2I, M2II, and M2III

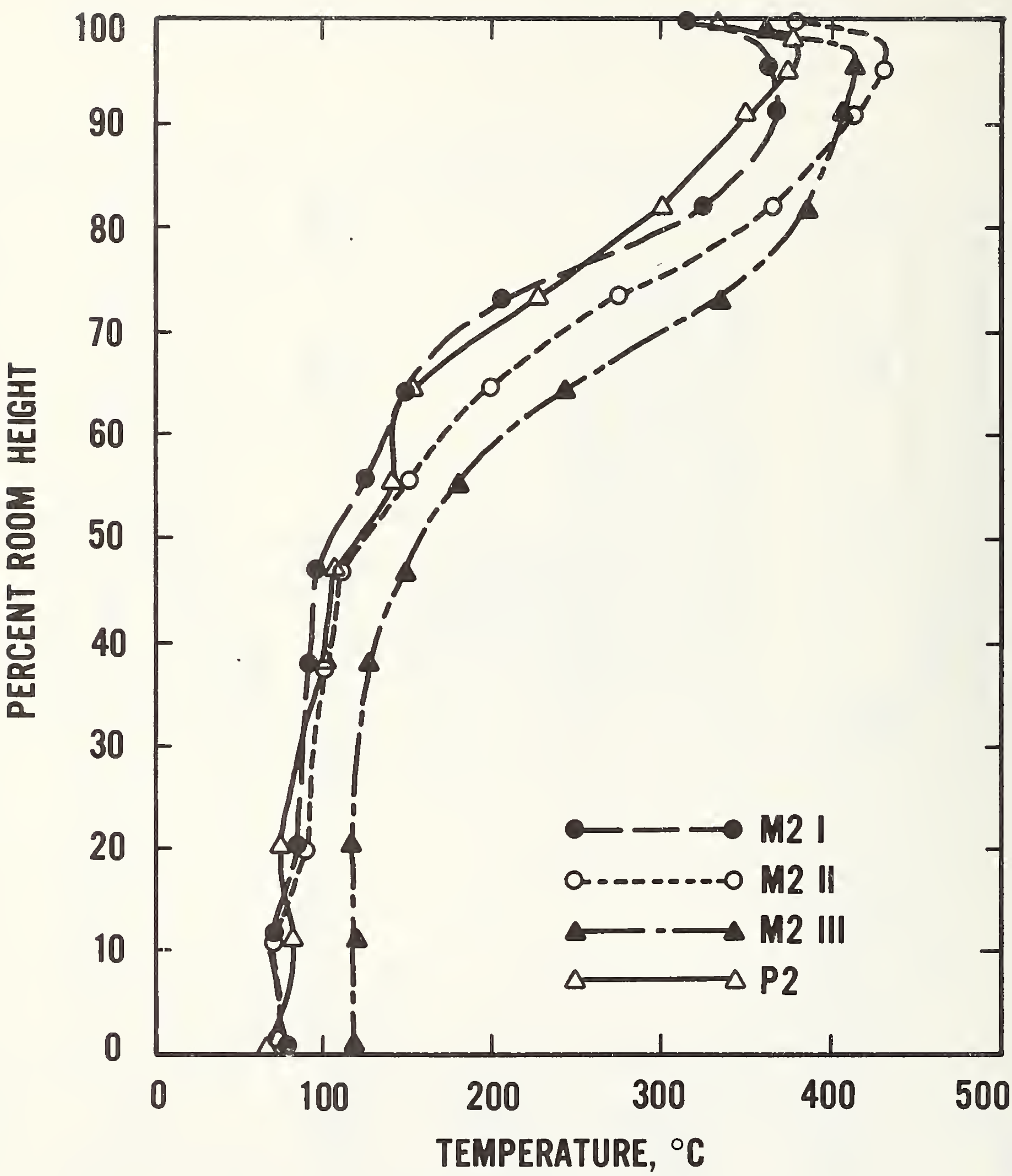

Figure 10. Room air temperature profiles at 240 s for full-scale fire P2 and model fires M2I, M2II, and M2III

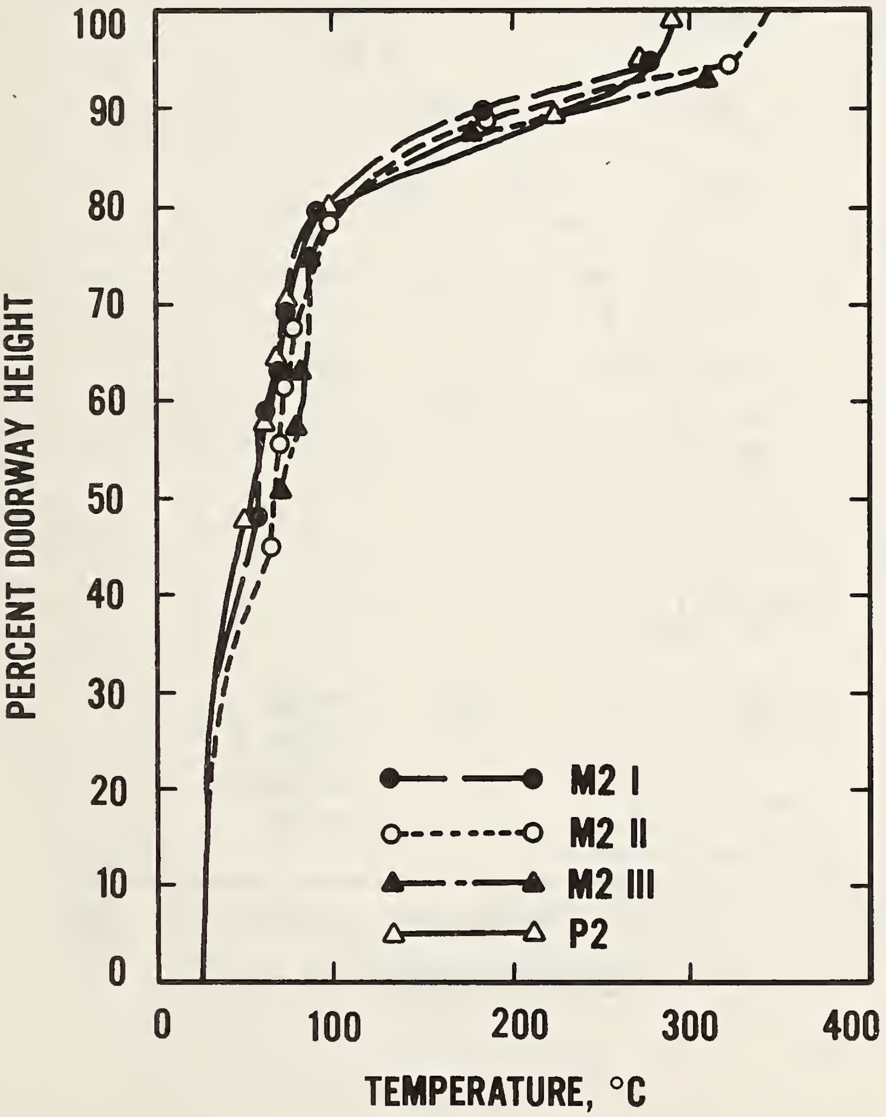

Figure 11. Doorway air temperature profiles at 240 s for full-scale fire P2 and model fires M2I, M2II, and M2III

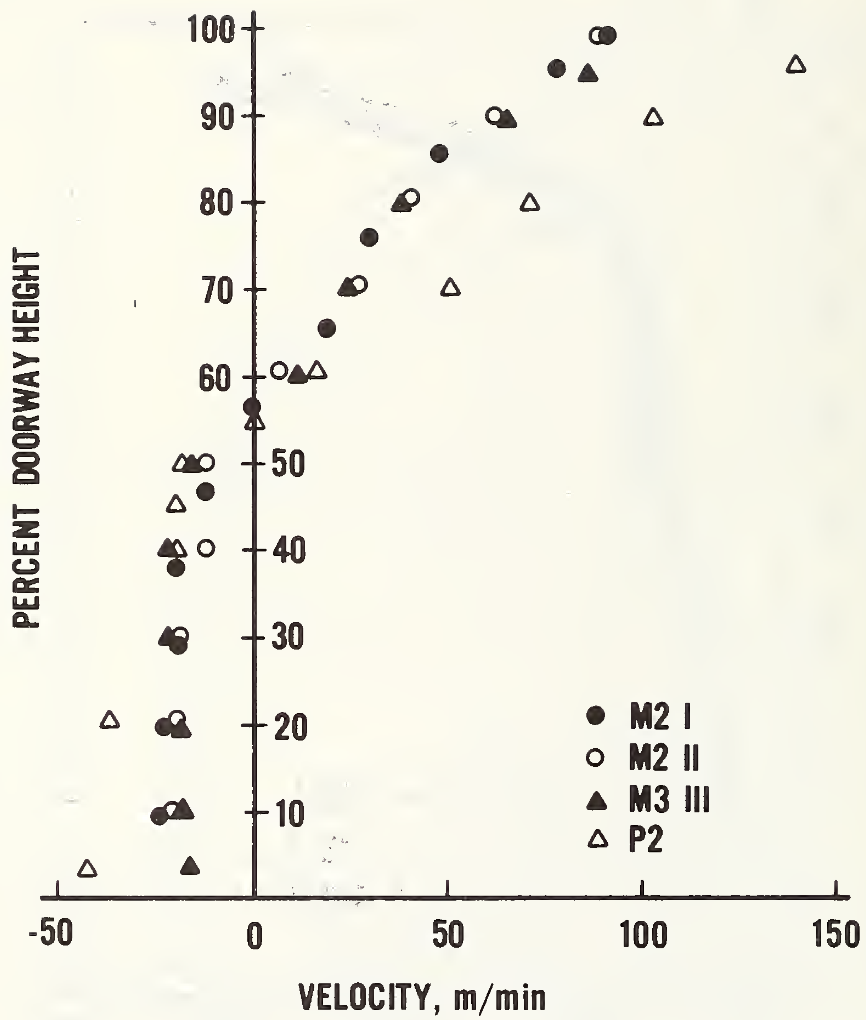

Figure 12. Doorway flow velocity profiles at 240 s for full-scale fire P2 and model fires M2I, M2II, and M2III

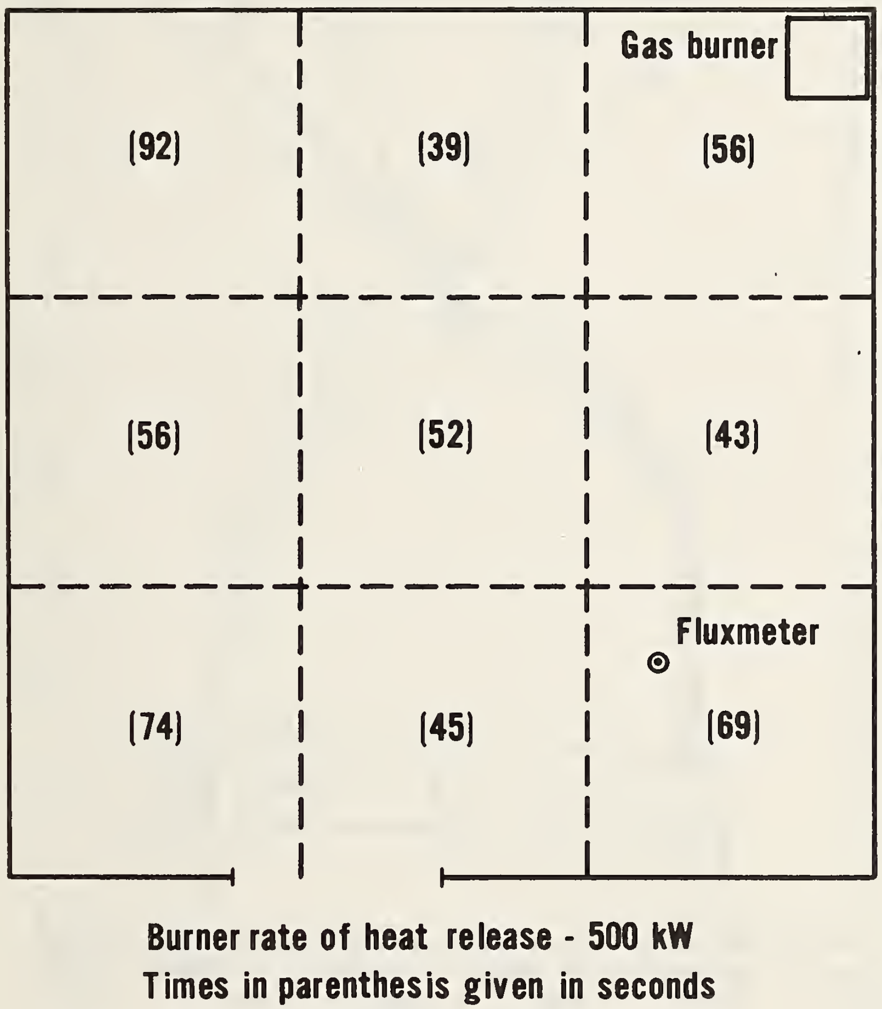

Figure 13. Ignition time of newspaper flashover indicators as a function of floor location

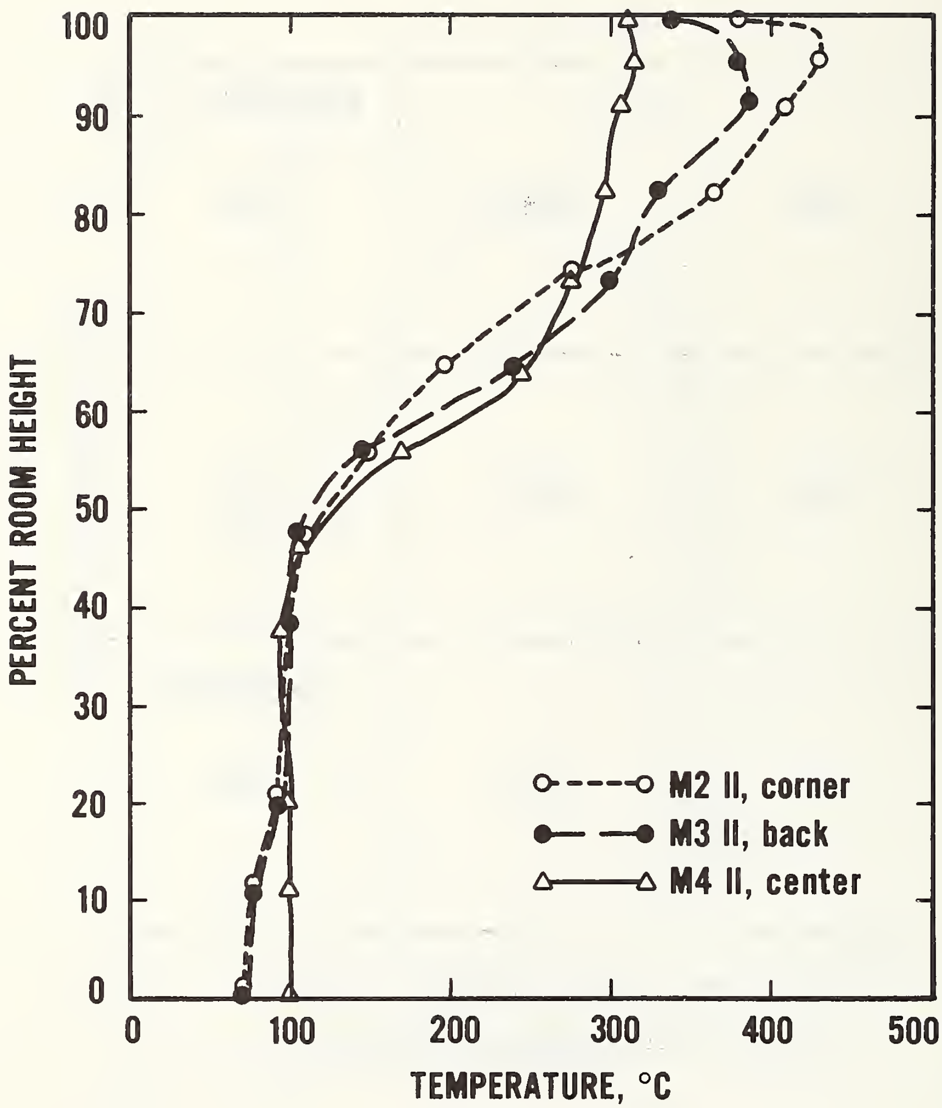

Figure 14. Model room air temperature profiles at 240 s for three burner locations

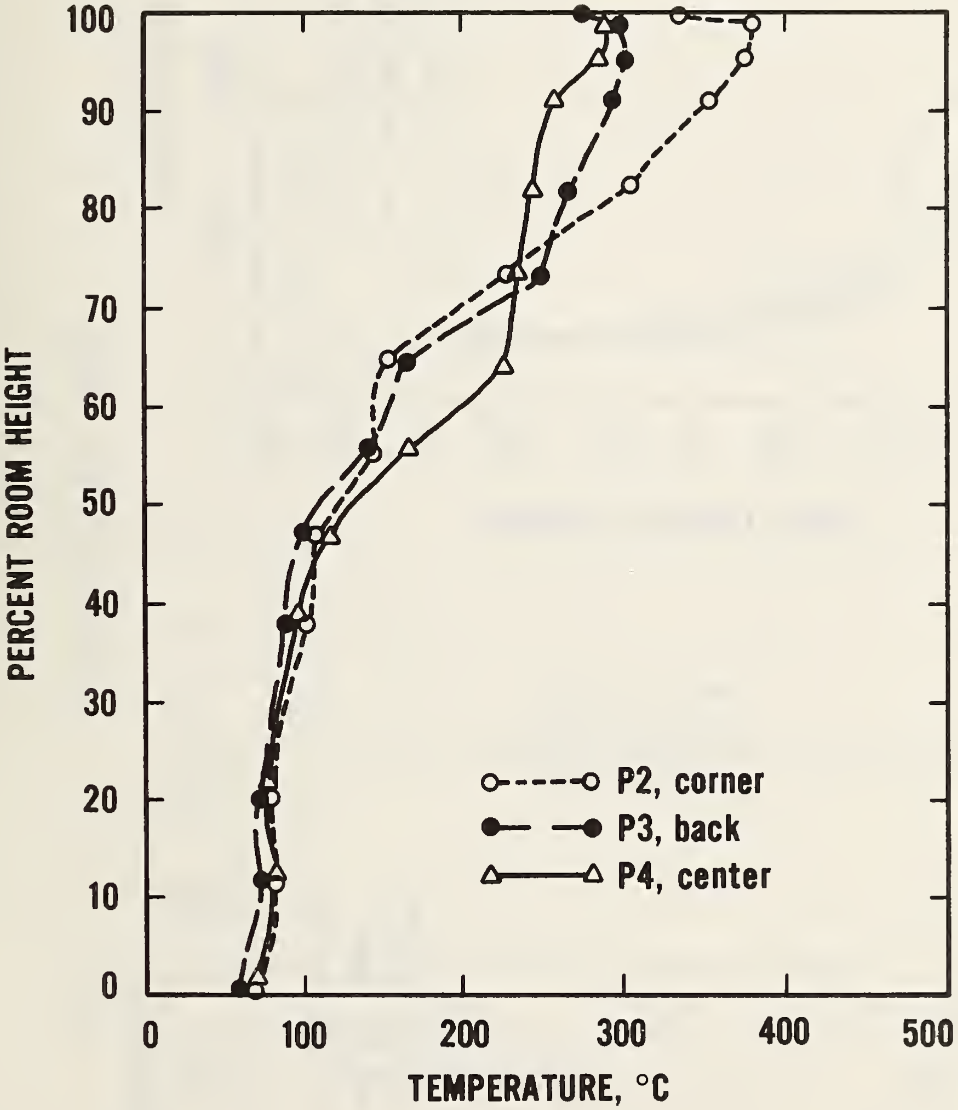

Figure 15. Full-scale room air temperature profiles at 240 s for three burner locations

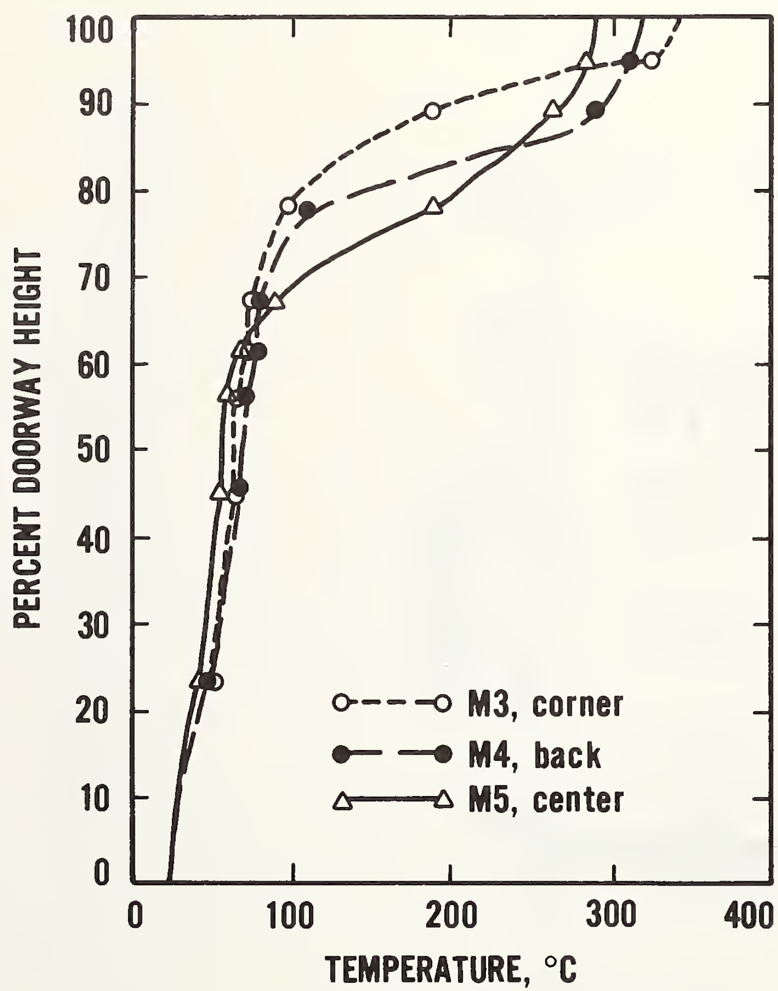

Figure 16. Model doorway air temperature profiles at 240 s for three burner locations

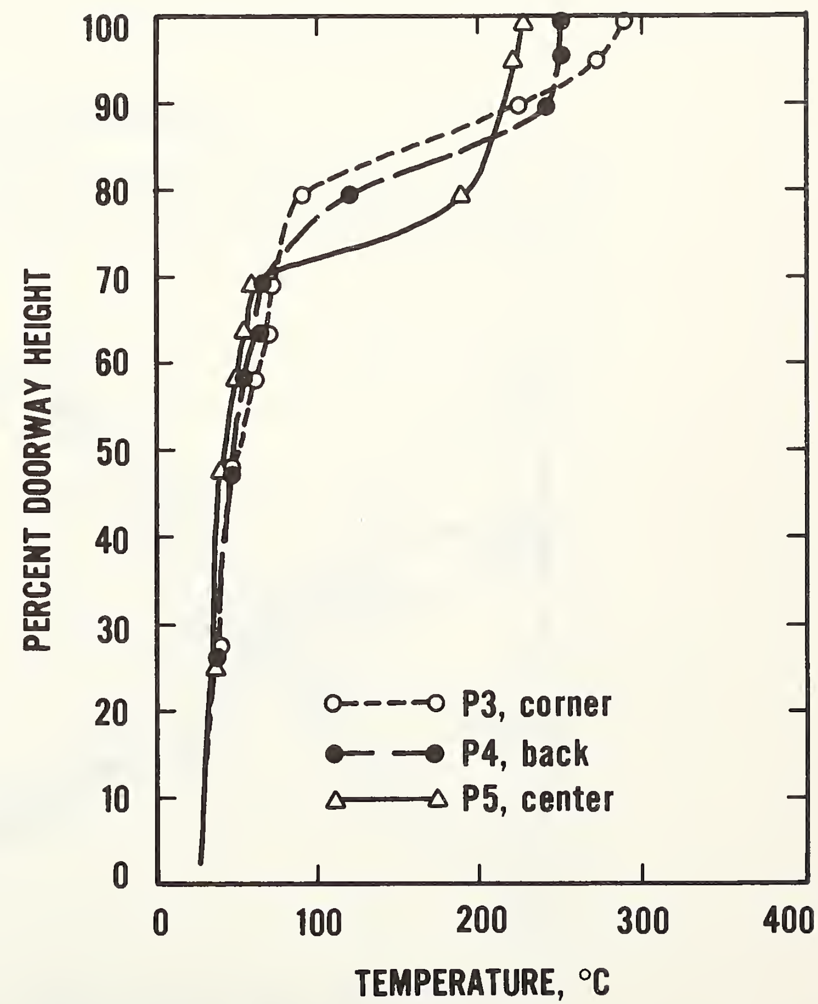

Figure 17. Full-scale doorway air temperature profiles at 240 s for three burner locations

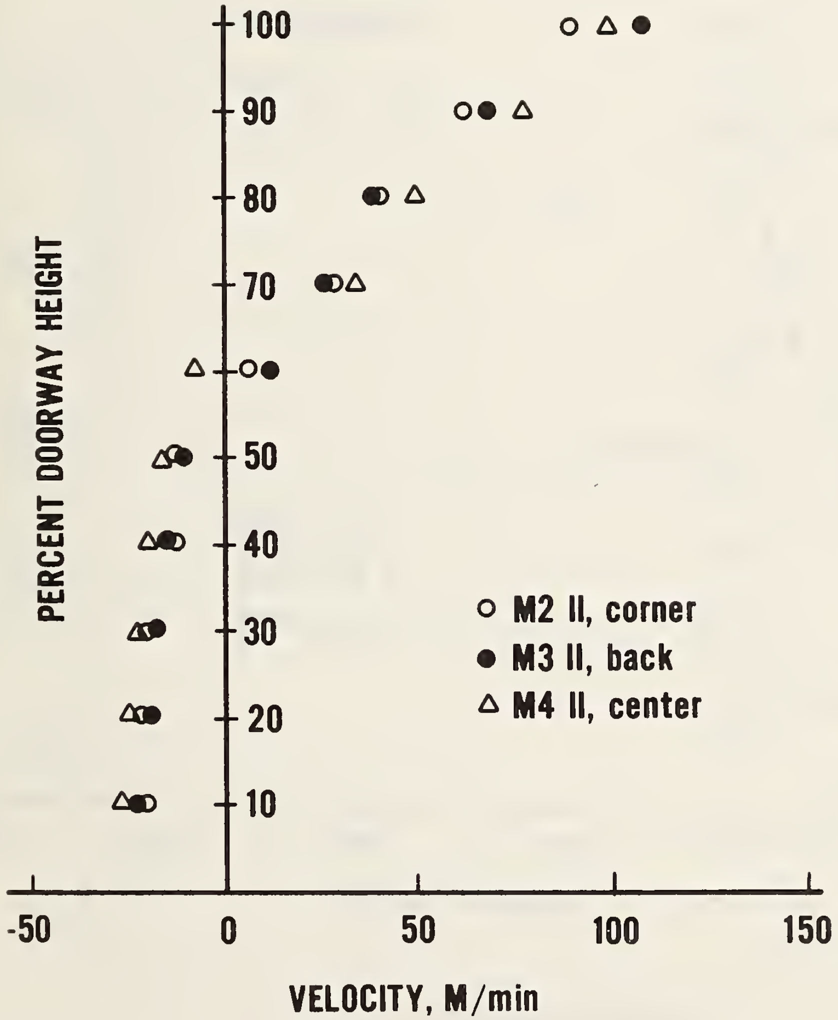

Figure 18. Model doorway flow velocity profiles at 240 s for three burner locations

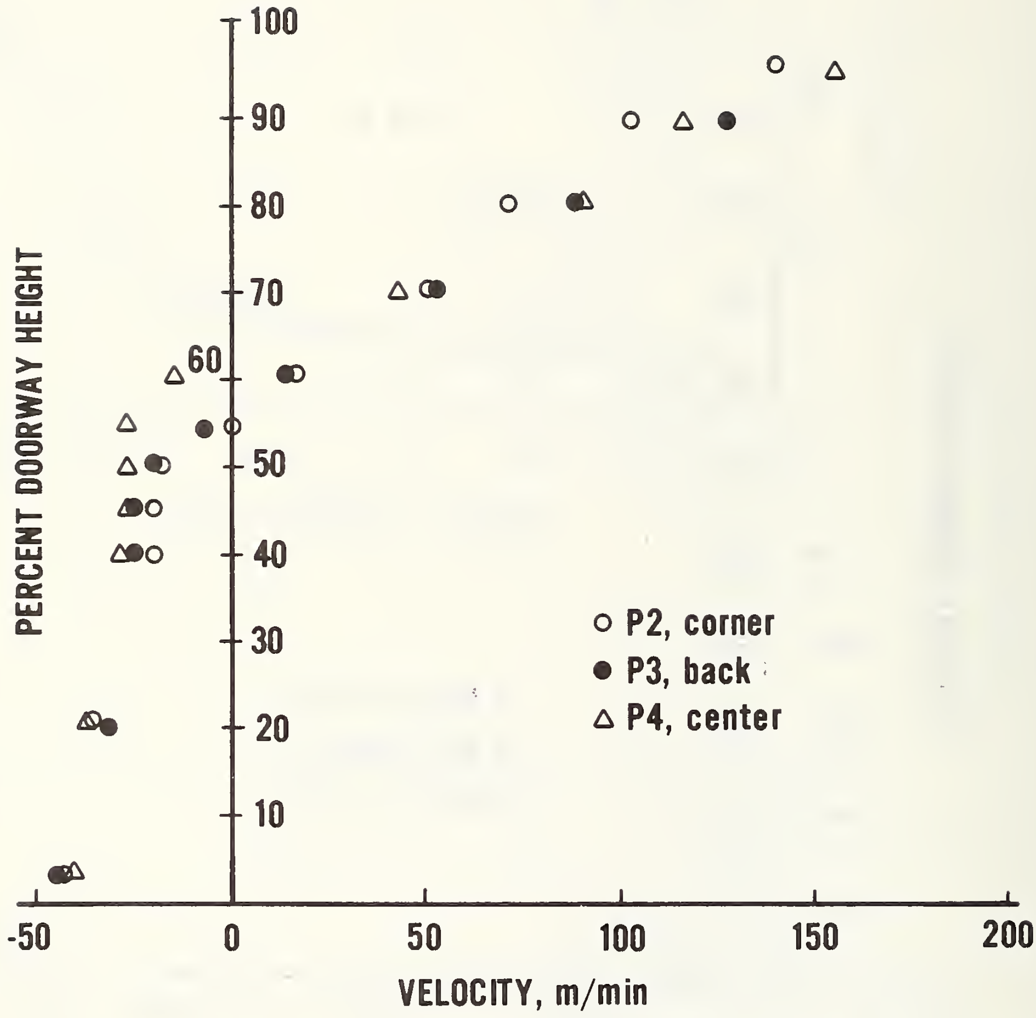

Figure 19. Full-scale doorway flow velocity profiles at 240 s for three burner locations

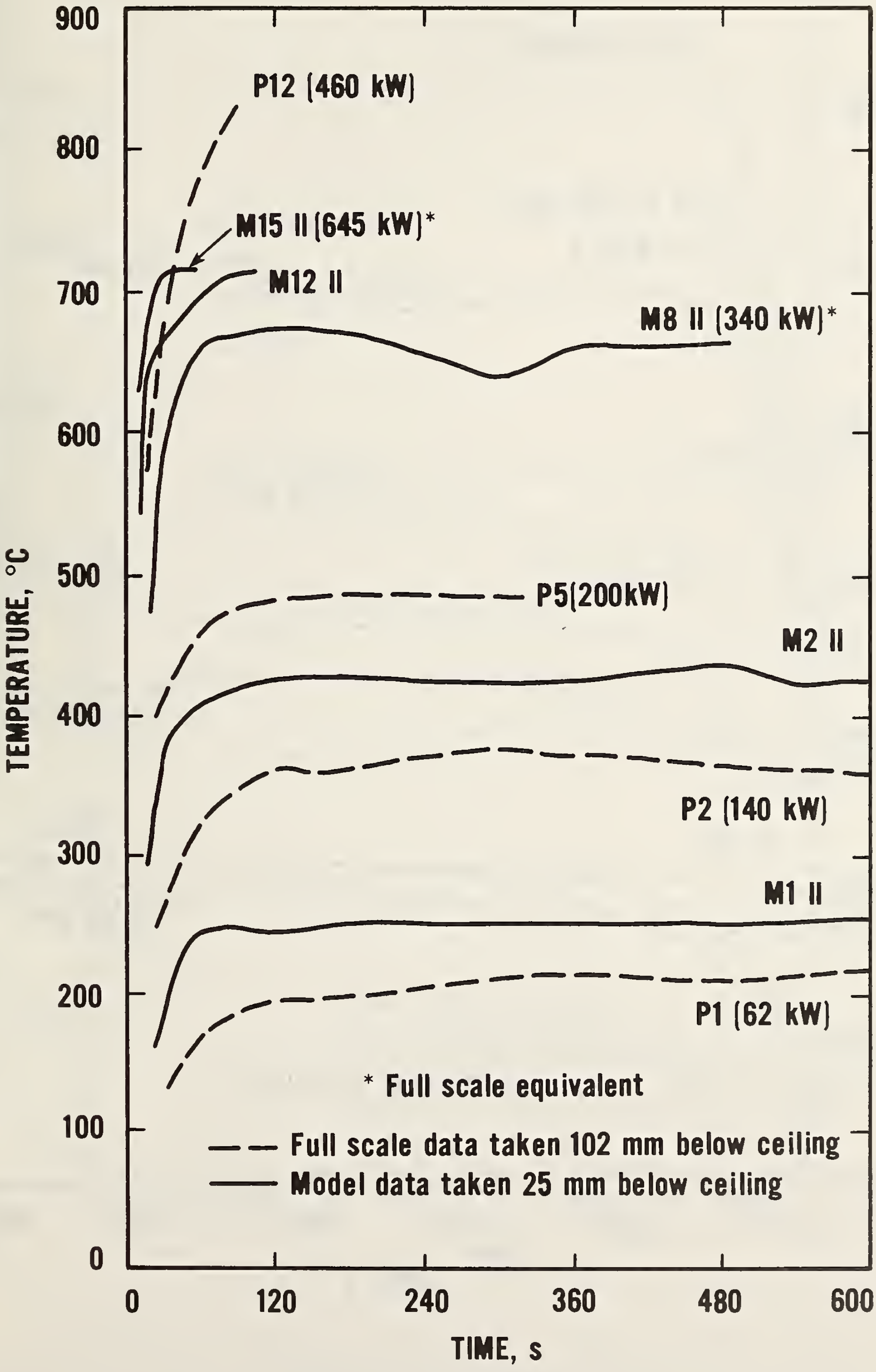

Figure 20. Model and full-scale room air temperature histories for fire source at back corner

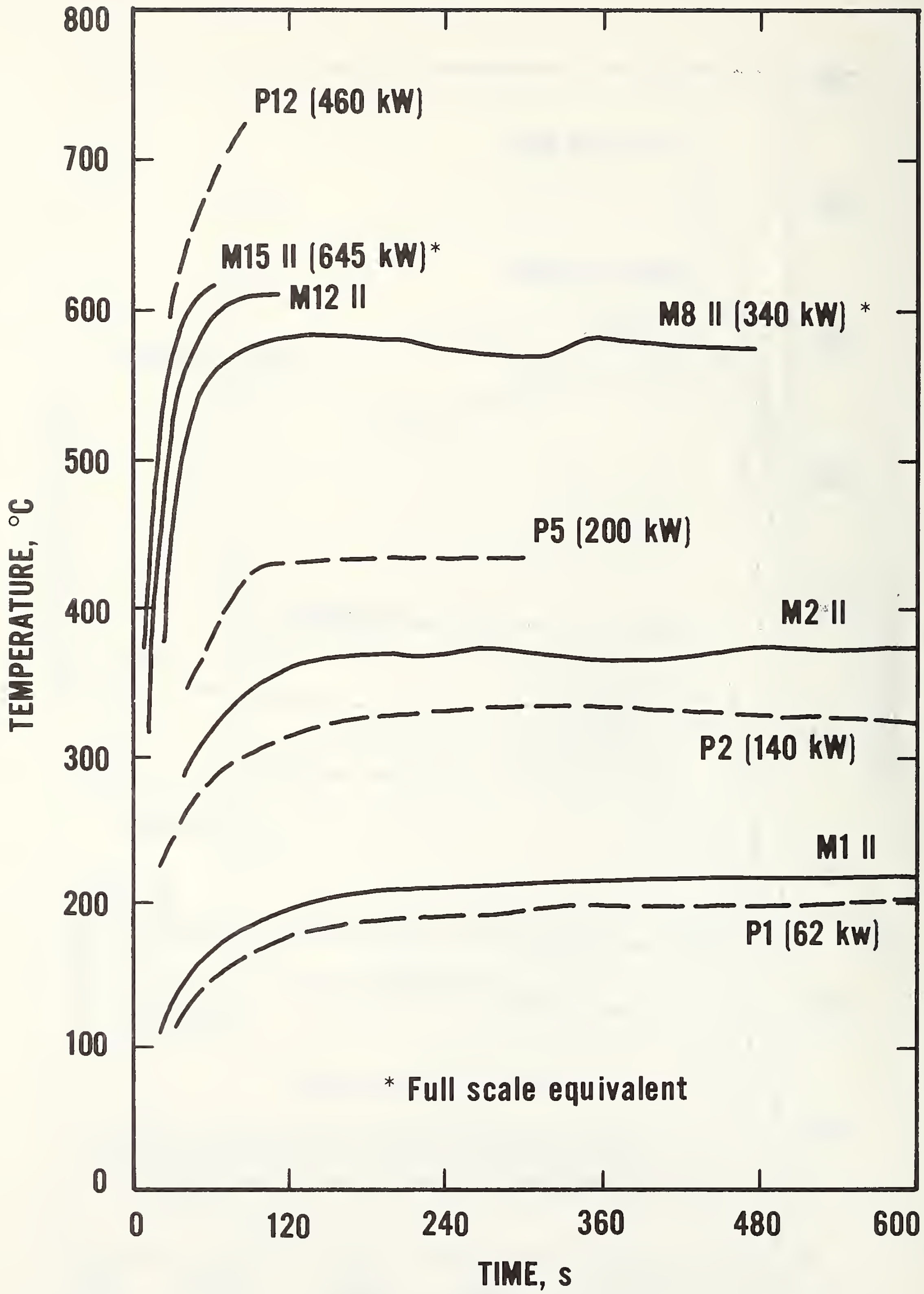

Figure 21. Model and full-scale ceiling temperature histories for fire source at back corner

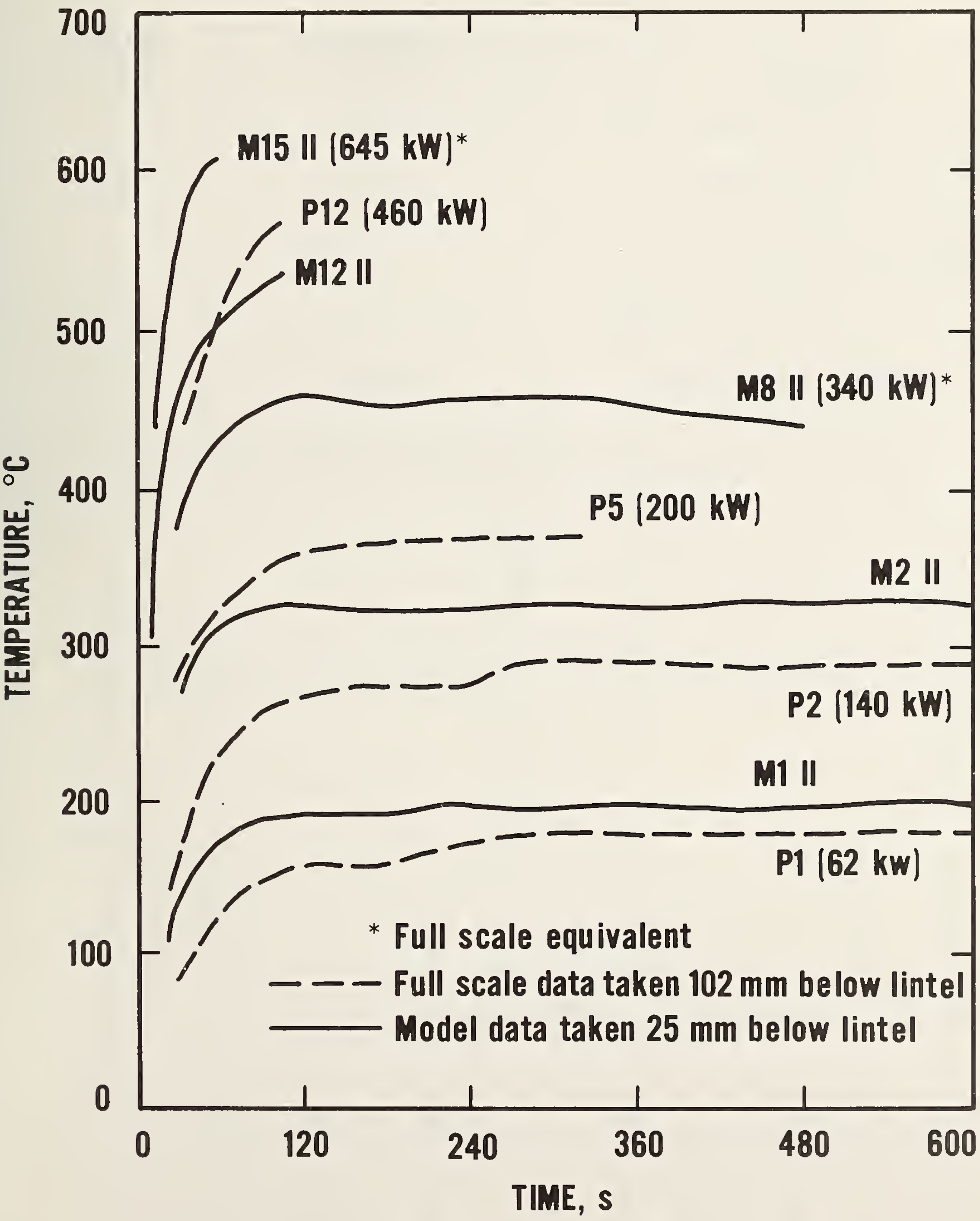

Figure 22. Model and full-scale doorway air temperature histories for fire source at back corner

Table 1. Interior finish materials used in room fire tests

Material	Thickness (mm)	Density (kg/m^3)
Nitrile Rubber Foam* B2	27	90
Nitrile Rubber Foam* C2	27	120
Fibrous Glass Insulation with Glass Cloth Facing	25	60
Printed Lauan Plywood Paneling	4	510
Intumescent Paint 0-987	0.25	900

* Polyvinyl chloride acrylonitrile butadiene closed cell foam

Table 2. Model doorway dimensions

Model Used to Test Nitrile Rubber Foam and Fibrous Glass Insulation

Lintel	Full-Scale	I	II	III
Scaled Lintel Depth*	Full-Size	One-Quarter	1.4 (One-Quarter)	1.8 (One-Quarter)
Lintel Depth (mm)	356	89	123	157
Doorway Height (mm)	1930	483	449	415
Doorway Width (mm)	732	366	406	460
Scaled Doorway Height	Full-Size	1.00**	0.93**	0.86**

Model Used to Test Plywood Paneling

Lintel	Full-Scale	I	II	III
Scaled Lintel Depth*	Full-Scale	One-Quarter	1.4 (One-Quarter)	1.8 (One-Quarter)
Lintel Depth (mm)	406	102	137	179
Doorway Height (mm)	2032	508	472	431
Doorway Width (mm)	762	381	426	492
Scaled Doorway Height	Full-Scale	1.00**	0.93**	0.85**

*Distance from the top of the doorway to surface of ceiling
**Value times one-quarter

Table 3. Summary of full-scale tests and counterpart model tests of nitrile rubber foam and plywood paneling

Test	Scale	Doorway Height	Insulation	Coating	Gas burner ignition source (kW)	Time to flame out doorway (s)	Max.* upper air temp. T_1 (°C)	Time to T_1 (s)	Max.** doorway temp. T_2 (°C)	Time to T_2 (s)	Ignition time of flashover indicator (s)
FS-1	Full	Full-size	C2	2 Coats A-207	62	27	774	30	572	30	30
6	1/4	Scaled	C2	2 Coats A-207	Scaled 62	< 45	647	42	-	-	45
23	1/4	0.93 Scaled	C2	2 Coats A-207	Scaled 62	54	683	56	598	64	64
FS-2	Full	Full-size	C2	None	62	32	829	30	630	30	30
4	1/4	Scaled	C2	None	Scaled 62	∞	216	600	215	438	∞
22	1/4	0.93 Scaled	C2	None	Scaled 62	38	707	43	585	43	43
33	1/4	0.86 Scaled	C2	None	Scaled 62	44	604	47	451	47	47
FS-3	Full	Full-size	B2	None	62	42	830	36	695	40	46
10	1/4	Scaled	B2	None	Scaled 62	∞	221	42	196	48	∞
24	1/4	0.93 Scaled	B2	None	Scaled 62	∞	410	162	288	186	∞
34	1/4	0.86 Scaled	B2	None	Scaled 62	88	646	90	500	97	97
FS-4	Full	Full-size	B2	2 Coats 0-987	94	∞	362	402	297	468	∞
44	1/4	0.93 Scaled	B2	2 Coats 0-987	Scaled 94	∞	398	462	288	360	∞
51	1/4	0.86 Scaled	B2	2 Coats 0-987	Scaled 94	∞	427	432	311	552	∞
PWFS-1	Full	Full-size	Plywood	None	90	190	766	178	-	-	∞
PWM-1	1/4	0.90 Scaled	Plywood	None	Scaled 90	188	790	180	-	-	∞
PWFS-2	Full	Full-size	Plywood	None	90	158	793	129	-	-	156
PWM-2	1/4	0.90	Plywood	None	Scaled 90	158	732	149	468	180	185 ***
PWM-3	1/4	Scaled	Plywood	None	Scaled 90	225	671	180	695	330	345
PWM-4	1/4	0.93	Plywood	None	Scaled 90	210	695	198	616	310	310
PWM-5	1/4	0.85	Plywood	None	Scaled 90	258	644	216	638	350	350

*Measured at 2.5 cm below center of ceiling
**Measured at 2.5 cm below top of doorway
***Only one flashover indicator ignited

Table 4. Summary of flashover times and temperatures in room fire tests with exposed fibrous glass insulation lining the walls and ceiling

Test: Model	Test: Full-Scale	Burner Position	Burner Gas*	Rate of Heat Release x $(scale)^2$ (kW)	Flashover Time (s)	Room** Air Temp. (°C)	Ceiling** Temp. (°C)	Doorway** Air Temp. (°C)
M1II		Corner	NG	62	None	255	214	198
	P1	Corner	P	62	None	209	192	172
M2I		Corner	NG	140	None	365	317	283
M2II		Corner	NG	140	None	428	380	327
M2III		Corner	NG	140	None	413	363	313
	P2	Corner	P	140	None	374	335	276
M3II		Back Wall	NG	140	None	380	339	313
	P3	Back Wall	P	140	None	302	276	259
M4II		Floor Center	NG	140	None	318	315	288
	P4	Floor Center	P	140	None	285	-	225
	P5	Corner	P	200	None	482	428	370
M6II		Corner	P	270	None	535	362	395
M7II		Corner	P	300	402	544	418	374
M8II		Corner	P	340	282	639	567	460
M9II		Corner	P	340	318	565	431	388
M10II		Back Wall	P	375	240	591	422	407
M11II		Back Wall	P	410	126	672	572	470
M12I		Corner	P	460	138	630	415	463
M12II		Corner	P	460	102	719	605	530
M12III		Corner	P	460	90	721	566	449
	P12	Corner	M	460	78	820	715	544
M13II		Floor Center	P	460	>480	612	545	524
M14II		Floor Center	P	475	138	581	444	429
M15II		Corner	P	645	45	718	592	583

*NG, P, and M refer to natural gas, propane, and methane, respectively.
**At time of flashover, otherwise at 240 s. For test M13II, temperatures given at 240 s.

Table 5. Comparison of fire buildup in full-scale and corresponding quarter-scale room fire tests of nitrile foam rubber

Insulation	Coating	Test No.	Doorway Lintel	Doorway Height	Ignition Setting	Degree of Fire Buildup*
C2	A-207	FS-1	-	Full-Size	Low	Flashover
		6	I	Scaled	Low	Flashover
		23	II	0.93 Scaled	Low	Flashover
C2	None	FS-2	-	Full-Size	Low	Flashover
		4	I	Scaled	Low	215°C
		22	II	0.93 Scaled	Low	Flashover
		33	III	0.86 Scaled	Low	Flashover
B2	None	FS-3	-	Full-Size	Low	Flashover
		10	I	Scaled	Low	196°C
		24	II	0.93 Scaled	Low	288°C
		34	III	0.86 Scaled	Low	Flashover
B2	0-987	FS-4	-	Full-Size	High	297°C
		44	II	0.93 Scaled	High	288°C
		51	III	0.86 Scaled	High	299°C

*Based on ignition of flashover indicator and doorway air temperature

Table 6. Flux measurements at time of flashover

Test	Time (s)	Floor (kW/m^2)	Upper Left Wall (kW/m^2)	Upper Right Wall (kW/m^2)	Ceiling (kW/m^2)
FS-1	30	17.3	-	-	-
23	64	20.0	49	55	50
FS-2	30	29.5	-	-	-
33	47	25.3	48	76	54
FS-3	46	20.0	-	-	-
24	186	2.8*	7.4*	6.7*	6.6*
34	97	25.2	56	67	52
FS-4	468	1.9*	-	-	-
44	360	4.6*	7.5*	-	-
51	552	5.6*	15*	13*	14*

*Flashover did not occur. Values given at the time of peak doorway temperature.

Table 7. Comparison of room air temperatures for fire tests with three different doorway openings

Test	Doorway height	Insulation	Source setting (kW)	Max. interior upper air temp. (°C)	Max. doorway air temp. (°C)	Flashover times (s)
4	Scaled	C2	3.9	216	215	∞
5*	Scaled	C2	3.9	293	213	∞
16	Scaled	C2	5.9	410	240	∞
17**	Scaled	C2	5.9	477	240	∞
22	0.93 Scaled	C2	3.9	707	585	43
33	0.86 Scaled	C2	3.9	604	451	47
10	Scaled	B2	3.9	221	196	∞
19	Scaled	B2	5.9	756	579	70
24	0.93 Scaled	B2	3.9	410	288	∞
34	0.86 Scaled	B2	3.9	646	500	97

*Repeat of test 4
**Repeat of test 16

Table 8. Summary of heat fluxes in room fire tests with fibrous glass insulation

Test		Burner	Rate of Heat	Flashover	Ceiling	Left Wall Flux* (kW/m^2)		Right Wall Flux* (kW/m^2)		Floor
Model	Full-Scale	Position	Release x $(scale)^2$ (kW)	Time (s)	Flux* (kW/m^2)	Sensor 1	Sensor 2	Sensor 1	Sensor 2	Flux (kW/m^2)
M1II		Corner	62	None	5.1	3.1	-	2.9	-	1.3
	P1	Corner	62	None	-	2.7	-	3.0	-	0.5
M2I		Corner	140	None	10.9	8.4	-	8.2	-	4.9
M2II		Corner	140	None	12.4	8.1	-	7.8	-	4.6
M2III		Corner	140	None	10.7	12.4	-	10.8	-	5.4
	P2	Corner	140	None	5.2	7.3	-	6.1	-	1.8
M3II		Back Wall	140	None	10.2	9.7	-	10.3	-	3.8
	P3	Back Wall	140	None	3.6	7.5	-	7.1	-	1.3
M4II		Floor Center	140	None	10.9	7.7	-	11.3	-	4.6
	P4	Floor Center	140	None	5.5	9.0	-	7.5	-	1.9
	P5	Corner	200	None	11.6	12.1	-	10.8	-	4.2
M6II		Corner	270	None	20.7	24.0	11.8	21.2	20.0	13.5
M7II		Corner	300	402	20.4	24.7	13.5	22.3	21.4	15.4
M8II		Corner	340	282	24.5	21.5	-	23.8	-	16.3
M9II		Corner	340	318	20.4	25.2	14.5	26.5	24.3	17.0
M10II		Back Wall	375	240	24.1	27.2	17.6	27.3	23.7	15.2
M11II		Back Wall	410	126	32.6	24.1	-	29.8	-	13.5
M12I		Corner	460	138	24.9	26.7	15.7	29.4	-	19.0
M12II		Corner	460	102	32.8	30.3	-	50.1	-	18.0
M12III		Corner	460	90	31.4	30.4	-	32.1	-	13.3
	P12	Corner	460	78	50.9	46.0	-	39.4	-	13.0
M13II		Floor Center	460	>480	52.5	23.0	-	32.3	-	19.9
M14II		Floor Center	475	138	39.3	32.1	21.1	24.0	-	20.2
M15II		Corner	645	45	38.1	36.3	-	52.1	-	18.7

*Data at time of flashover, otherwise at 240 s. For test M13II, data given at 240 s. Sensor 1 at 3/4 room height. Sensor 2 at 5/8 room height.

Table 9. Doorway flow velocities in fire tests with fibrous glass insulation

% Doorway Heights * (Velocities ** in m/min)

Test	3	10	20	30	40	45	50	55	60	65	70	75	80	85	90	95	99
M1II		-17															
P1	-31																
M2I		-25	-25	-20	-20	-14		0		17		29		47		77	91
M2II		-20	-20	-19	-13		-13		6		26		39		61		88
M2III	-15	-17	-19	-20	-21		-16		11		24		38		66	87	
P2	-41		-37		-21	-20	-18	0	16		50		70		103	140	
M3II		-21	-20	-18	-15		- 9		12		25		37		68		108
P3	-45		-33		-25	-26	-20	- 8	14		51		88		127		
M4II		-27	-24	-22	-20		-16		- 7		34		48		77		100
P4	-41		-38		-28	-26	-28	-26	-15		42		90		114	155	
M12II		-26															
P12	-53																

* Velocities measured at positions different from those indicated are grouped under the nearest locations shown.
** Negative values denote inflow.

Table 10. Comparison of flashover and flameover times (s) for full-scale and quarter-scale tests

Material	Full-Scale Test	Quarter-Scale Test	Flashover		Flameover***	
			Full-Scale	Quarter-Scale	Full-Scale	Quarter-Scale
Nitrile Rubber Foam C2, A-207 Coating	FS-1	23	30	64	27	54
Nitrile Rubber Foam C2	FS-2	33	30	47	32	44
Nitrile Rubber Foam B2	FS-3	34	46	97	42	88
Nitrile Rubber Foam B2, 0-987 Coating	FS-4	51	None	None	None	None
Plywood	PWFS-1	PWM-1	None	None	190	188
Plywood	PWFS-2	PWM-2	158	185**	158	158
Fibrous Glass, Glass Cloth Facing	P12	M12III	78	90	-	-
Polyurethane (FSC 200)*	-	-	13	18	11	15
Polyurethane (FSC 60)*	-	-	14	19	12	15
Polyurethane (FSC 30)*	-	-	18	32	17	29
Polyisocyanurate (FSC < 25)*	-	-	368	None	370	None
Polyisocyanurate, foil faced (FSC < 25)*	-	-	None	None	None	None
Fiber Board (FSC < 25)*	-	-	None	None	None	None
Fibrous Glass, Unfaced (FSC < 25)*	-	-	None	None	None	None

*FSC xx refers to a flame spread classification of xx from the ASTM E 84 test.
**Only one flashover indicator ignited.
***Time for flames to extend beyond the doorway.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

A technique for modeling fire build-up in rooms with combustible interior finish was refined to achieve closer simulation of full-scale fire development. Fire experiments were performed in one-quarter scale model rooms and full-scale rooms having a doorway opening. The interior finish test materials were nitrile foam rubber, fibrous glass, and plywood; a gas burner was employed as the fire source in a rear corner of the room. It was necessary to lower the doorway opening in the model by as much as 14 percent to obtain flashover with the same equivalent heating rate that produced flashover in the full-scale test. At the same time, the width of the doorway in the model was increased appropriately to maintain the same volumetric air flow rate. The effects of burner location and heating rate on flashover in a well-insulated room were also studied to help select a suitable ignition source size and placement for testing of interior finish materials. The minimum heating rate needed to cause flashover in a 3 x 3 x 2.3 m high room lined with fibrous glass and having a 0.73 x 1.93 m high doorway opening would entail placement of the heat source in a back corner with the source having a heat release rate of 300 kW. A corresponding rate for the quarter-scale room would be 19 kW.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Fire growth; flashover; heat release rate; physical modeling; room fires; scale models

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